AMURA ANNAMARIA — TESI DI DOTTORATO — 2019/2020

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UNIVERSITÀ
DEGLI STUDI
DI URBINO
CARLO BO

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CORSO DI DOTTORATO DI RICERCA IN SCIENZE DI BASE E APPLICAZIONI
Curriculum SCIENZE DELLA COMPLESSITÀ

XXXIII CICLO

# DESIGN OF A SEMI-AUTOMATIC METHODOLOGY SUPPORTING THE GRAPHIC DOCUMENTATION FOR THE RESTORATION OF ARTIFACTS.

Settore Scientifico Disciplinare INF-01, ICAR-17




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Chiar.mo Prof. Alessandro Aldini

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# Abstact

To motivate the proposed research, it is necessary to clearly define the role and usefulness in cultural heritage of the two main topics dealt with: graphic documentation and diagnostic imaging.

The geometric-dimensional cognition of the object of historical-artistic interest and the study of its constituent materials have a fundamental role in all the disciplines concerning the activity of preservation and conservation (or restoration)[1]. They represent a unique opportunity to transcribe reality through graphic and photographic interpretation. Hand drawing and diagnostic imaging are the instruments with which the conservator-restorer interrogates the artefact, transforming dialogue into a process of representation, giving at graphic and photography, not the role of expressive tools but languages focused on the methodological developments expressed by the culture of restoration. Photographic and graphic documentation, diagnostic investigations together with the conservation/technical report and written report, *"represent a "dossier" still considered the current standard for all interventions performed on artefacts to allow the recognition and definition of each procedure carried out, leaving an organized description of that done today to allow a proper maintenance of that artefact tomorrow, providing the basis for any new restoration and communicating the additional knowledge obtained in the restoration process" [Translation] - (Sacco, 2002, p.28).*

1 In this paper, the term *preservation* will be used to indicate planned maintenance performed on the artefacts, for example, all interventions aimed at preserving their microclimate, elimination of surface debris such as fine particles, etc. The term *conservation* will instead be used to indicate direct restoration interventions on the artefacts.



Numerous factors contribute to the realization of appropriate graphic documentation and involve problems of theoretical and methodological nature. What must be recorded is the set of aesthetic, static, technical, and historical parameters, as well as those relevant to the preservation conditions. It is often necessary to define for each case the system of consistency of all the measures taken, choosing different schedules, modalities and operational criteria of a technical/executive type, depending on the object to be documented [1]. In addition to the listed factors, there are also difficulties related to the interpretation of diagnostic images that are currently visually inspected with the naked eye by conservator-restorers, or at most optimized through pre-processing by diagnosticians. The detected characteristics are concurrently manually reported in ad hoc graphic surveys, denominated *Graphic Documentation*.

The software tools currently used to support these tasks only allow the manual tracing of drawings on a photographic basis, thus making this process subjective, challenging, and time-consuming. The complexity of the whole process induces conservator-restorers to only record essential information, rendering their documentation incomplete and far from ensuring the reproducibility of the results.

To date, as far as the automatic extraction of drawings from raster images is concerned, a specific technique has been adopted only in the archaeological field. It is developed to produce illustrations in raster format, extracted from photographs of archaeological objects [2],[3]. Unfortunately, these drawing extraction techniques do not meet the requirements of graphic documentation in restoration, which instead requires the design of a non-illustrative, non-raster vector drawing, i.e., without shading and with topographically coherent closed polygons.

The aim of this research is to propose a semi-automated methodology based on the use of image analysis algorithms that may help cultural heritage operators interpret diagnostic images, recording their findings and performing image analysis through statistical methods. The set of relevant available images can be handled as a whole, and the *regions of interest* (ROI) segmented and extracted by Blind Source Separation Methods (BSS) and binarization. Then, region boundaries are vectorized to allow the graphic documentation and statistical analysis of results. The procedure facilitates conservator-restorers' work, making it faster and less subjective, allowing them the freedom to choose what is essential to their purpos-

es from the wealth of information that is automatically extracted from the images. These computerized processing procedures, defined as morphological and segmentation procedures, allow images to be divided into their constituent objects, though not ensuring optimal results in all fields of application. Their accuracy and ease in identification are closely linked to variations in the following characteristics:

- edge models that distinguish objects;
- similarities between regions;
- spatial resolution in pixels;
- bit depth per channel;
- color pattern/space.

Various identification problems also occur according to the type of artefact and the formal geometric requirements that conservation and restoration interventions may require.

The different phases of the methodology are supported by two software applications: QGIS, a Geographic Information System (GIS) application, and Matlab. The results are comparable and compatible with currently used Computer-Aided Drafting (CAD) software and SICAR.

The thesis is organized as follows.

Chapter 1 presents the birth and development of documentation in the field of cultural heritage, analyzing specific regulations on the matter and various applications. In addition, the current graphic and thematic information structure, and software currently used to create and manage such information, are described.

In chapter 2 we discuss still unsolved problems concerning graphic documentation and diagnostic image analysis. A list of studies and researches aimed at solving such problems is also included.

Chapter 3 illustrates the theoretic principles on which the proposed methodology is based and presents reasons and reflections which led to its definition. The software applications (MatLab and QGIS) selected to practically carry out the methodology itself are also analyzed.

In chapter 4, the methodology structure is presented and described: each section presents a brief introductory description and an applicative part in which some steps of the chosen software applications are briefly demonstrated.

To show the outcome of methodology application, chapter 5 presents the results obtained in real study cases.

CHAPTER I

# Documentation for the Restoration and Conservation of Cultural Heritage

The term *documentation* refers to the activity of systematic collection of information derived from the diagnostic investigation, preservation-monitoring, conservation, and restoration, performed on cultural property. Such information is acquired in an increasing variety of formats generated by the different analysis and recording techniques including texts, images, graphic documentation, photographic documentation, diagnostic investigations, and 3D models. Specifically, graphic documentation, also called graphic survey or *Thematic Maps*, represents the primary tool to communicate and summarize the information collected on the nature and condition of an artefact, which is transcribed into geometrically correct drawings and translated into conventional graphic symbols [4]. Professionals operating in different times and modalities use Thematic Maps as the formal and unequivocal means of communication, comparison and guidance for successive conservation operations. They should be easily accessible, readable, and usable. An artefact's documentation acquires a cyclical and continuous character: each restoration leads to the acquisition of new information that requires to be regularly recorded in new documentation. In brief, graphical documentation represents a database that must be updated in real-time and correlated with other data; it must satisfy three purposes: acquire, release and store specific information; and it must be part of a continuous cycle summarized in three actions: discover, document, intervene [5].

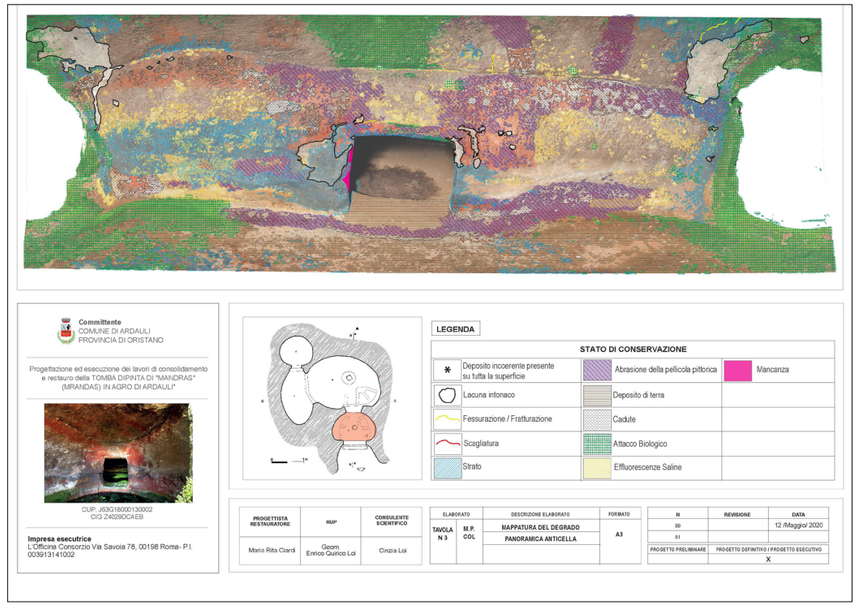



Figure 1.1
Example of Graphic Documentation. Thematic maps of the conservation status of a painted Neolithic Tomb. Source: Executive restoration project of Officina Consorzio, (Rome) for the Superintendence of the town of Oristano in Sardinia.

Section 1.1

# Historical notes: the origin of graphic and photographic language for documentation

It can be asserted that graphic documentation was born from the encounter with the discipline of architectural surveys, which has taken on different connotations over the centuries finding an increasing correspondence with the needs of preservation, conservation, and restoration of any artefact. Since the eighteenth century, as a result of the first archaeological finds of Herculaneum and Pompeii, a culture of the ancient became widespread and archaeology was born as a discipline [6]. In this new climate of discovery of antiquities a different approach to architecture arose, as it became the object of study and surveyal for many researchers, mostly French and German. This period was characterized by a robust theoretical commitment, the birth of new academic models, the establishment of new schools and the publication of drawings and treatises.

The survey campaigns were considered indispensable by the vocational training academies and corresponded to the birth of *realistic/documentary vedutism*: the images had to satisfy archaeological interests, historians or scientists with subsequent publication of specific collections and essays. Thus, a graphic expression was born, formed by new methods of representation that adopted perspective rules of descriptive geometry, alternating drawings full of virtuosity and chiaroscuro effects, to a trait capable of representing historical architecture more objectively, and describing the status of degradation in its urban and landscape context.[7]. The main execution techniques created a strong integration between drawing and painting and meticulously analyzed the material and structural data with the expectation of reproducing reality as faithfully as possible.

These representations proved to be essential for the spread of archaeological culture and favored the birth of the first interventions of “restoration.”

At the beginning of the nineteenth century, the conception of landscape and architecture changed from aesthetic to scientific, passing from artistic and poetic readings to geography and topographical descriptions. Until that time, documentation had been entirely reliant on manual drawing, then depictions began to be aided by the use of optical cameras specific for the realization of perspective views (camera obscura), anticipating the approach of photography and engendering a slow metamorphosis in representation. In addition to improvements in graphic rendering and representation methodologies, there was also a refining of existing measuring instruments and the use of new instruments coming from the natural astronomical sciences. The lithographic technique was also used to reproduce architecture and documents. It was one of the first concrete manifestations of a technical reproducibility of art, allowing for the creation of print catalogues of great interest, contributing to the diffusion of scientific illustrations, making the still fundamental intermediation between painting and photography possible, through graphics [8][9]. The techniques of color engraving, aquatint and lithography were used long after the invention of photography, which reached Italy in the same year of its invention, 1839. Photography rapidly became an alternative to various manual techniques. It was the French State, in particular the *Direction des Biens Artistiques*, that recognized the importance of the photographic process in documentation by establishing the first photographic society in 1851, *La Société heliographique* and, in the same year, thanks to the subsidies of the *Commission des monuments historiques* (CMH), the first public Photographic commission was made: *La mission héliographique.* The CMH, a public institution founded in 1837 to preserve French heritage, followed with great attention the development of photography identifying it as a more precise tool than drawing for obtaining representations of buildings of interest [10].

Photographs were used for objective historical and topographical documentation. In Italy, the Alinari Brothers were the first to “classify” architecture with an encyclopedic knowledge project from 1852, while the Borghi family specialized in the reproduction of works of art, undertaking several photographic campaigns in Italy and starting a commercial venture, in Naples in 1879. Mostly, daguerre-

**Charters of Restoration**
*Athens Charter (1931)*
*Italian Charter (1932)*
*Venice Charter (1964)*
*Italian Charter (1972)*
*Amsterdam Charter (1975)*
*Washington Charter (1987)*
*Krakow Charter (2000)*

***Athens Charter 1931***
point VIII.2 "*Each country should constitute official records which shall contain all documents relating to its historic monuments*"
***Italian Charter 1932***
Point 9: "...the experimental aids of the various sciences must be used to contribute to the conservation of the dilapidated structures, and empirical procedures should give way to those more rigidly scientific."
Point 10: *"That both in the archaeological excavation, and in the restoration of monuments, it is an essential and rigidly fixed condition, that precise documentation accompanies the work through analytical reports collected in a restoration journal and illustrated by drawings and photographs, so that all the determining elements in the structure and shape of the monument, and all the recomposing, liberation and completion phases, are acquired permanently and safely.*

otypes were used for the reproduction of pictorial works, often for practical and private reasons. For example, by artists wanting to keep an image of works destined for distant clients, or by collectors and art dealers for exchanges and presentations of collections. Between Florence, Rome, and Naples, a circuit of artists and photographers of international renown arose, some of them experimenting with reproduction techniques for very complex artistic and architectural artefacts. Lorenzo Suscipj assembled the first Italian panorama in 1841 from San Pietro in Montorio, Rome, using eight daguerreotypes. Scotsman Robert Macpherson specialized in reproducing paintings and architecture, taking great care over technical aspects, obtaining, in 1853, the first patent for photo-engraving techniques (from the Italian Ministry of Commerce, Fine Arts, Industry, and Agriculture), taking 300 photos of sculptures from the Vatican Museums. In Naples, Alphonse Bernoud became the official photographer of the Bourbons. Giovanni Gargiolli, engineer, architect, inventor, and photographer (creator in 1888, with his other aristocratic friends, of the "*Association of photography amateurs*" the first of its kind in Italy) in 1890 suggested the establishment of a photographic laboratory dedicated to the reproduction of monuments, to be directed by the Ministry of Education. In 1895 he was given the task of taking photographs for the Technical Office of Monuments in Rome although his Photographic Laboratory was given legal form only in 1913. Regardless of any institutional arrangements, the activity soon became widespread throughout the Italian territory: at the service of the General Directorate of Antiquities and Fine Arts or museum and excavation directors in collaboration with scholars of great fame such as Pietro Toesca and Adolfo Venturi [9].

## 1.1.1 The Charters of Restoration and the creation of the Central Institute

Until the mid-nineteenth century, the predominant conception of *restoration* was reconstructing, recovery and reprocessing of ancient techniques. Interventions were often carried out by artists and craftsmen in the absence of professional, scientific training. The works received conservation interventions only if they reflected aesthetic, religious, or political prestige.The sole purpose of these interventions was to maintain in good condition the "meaning" of the work and its "readability" or "practicability." Unfortunately, in the absence of a historical and aesthetic reflection, often, both the appearance and the content of the works submitted to such interventions varied according to the aesthetic conceptions of different historical periods [11]. Beginning in 1883, there were several attempts to bring together all the professional figures related to the world of restoration through the planning of congresses. These events conducted to a complex and gradual elaboration of principles and prescriptions, later codified and incorporated into a series of documents aimed at guiding interventions, the so-called "*Charters of Restoration*" [12], with the definition of the first ministerial laws and decrees from the early 1880s [13]. The first regulations issued regarding such documentation were closely linked to the architectural monuments, but the general norms could easily be extended to any restoration, also of pictorial and sculptural artefacts. Analyzing various points from the *Athens Charter* in 1931 to the *Krakow Charter* in 2000, we can identify the different approaches to documentation and scientific restoration. The *Italian Restoration Charter* of 1932 can be considered the first official directive of the Italian state in the matter of restoration. The principles it affirmed were similar to the *Athens Charter***,** with the addition of some innovative thought by Gustavo Giovannoni (1873-1947), who was the first to define the concept of *"scientific restoration"*, suggesting that each restoration intervention should exploit all the most modern technologies to perform scientific interventions [14], [15].

The importance of documentation was already enunciated at the beginning of the Charters of Restoration and understood as a record of the operations performed on the artefact and the collection of all the material related to the property in question. Because of its enormous value in knowledge, every state required the correct storage of this material. In 1969, the Central Office for the Catalogue, under the General Directorate of Antiquities and Fine Arts, was established as part of the Ministry of Education. This archive is of great importance for the history of cataloging in Italy as it is the first organic attempt to census the most important monuments and works of art preserved in public buildings. The oldest documentary reports are following the enactment of the laws of protection of the Kingdom of Italy at the end of the nineteenth century. Those that accompanied the interventions had a large part reserved to the description where you could report the



***Venice Charter 1964***
Art. 2 *"The conservation and restoration of monuments constitutes a discipline which is valid for all the sciences and all the techniques which can contribute to the study and the safeguard of the monumental patrimony."*
Art. 16 *"The Conservation, restoration, and excavation work will always be accompanied by rigorous documentation, with analytical and critical reports, illustrated by drawings and photographs. All phases of liberation work, such as the technical and formal elements identified during the work, will be included. This documentation will be deposited in public archives and will be made available to scholars. Its publication is highly recommended."*

The census began with the establishment of the Directorate of Excavations and Museums of the Kingdom (1875) In 1881 it was transformed into the General Directorate of Antiquities and Fine Arts. The importance of attaching the cataloguing card with graphic and/or photographic documentation was reaffirmed by Roberto Longhi at the Convention of the Superintendents in 1938.

design of the artefact. Starting from the 1920s there were already several models of cards in use, some had pencil or ink drawings on the first side or attached, others were accompanied by plans and photographs glued or attached. The drawings of the object could initially be just rough sketches or focused on a realistic vision that emulated, in a similar way to a photo frame, the material consistency of the work.The activity of the *Gabinetto Fotografico Nazionale* was also linked to the census activity, established in 1895 with the aim of making photographic reproductions of the immovable and movable artistic material existing in the Kingdom and the Colonies, and to provide for the preservation of the photographic material necessary for cataloging.

In Italy, awareness of the dangers to which the artefacts were exposed through a restoration conducted without precise technical criteria, conducted in 1939 to the foundation in Rome -at the suggestion of Giulio Carlo Argan- of the *Central Restoration Institute for artefact,* directed from its beginnings until 1959 by Cesare Brandi, (today *Higher Institute for Conservation and Restoration -ISCR*)[1].

A Ministerial Commission was appointed to draw up unified standards that, starting from archaeology, would cover all branches of the figurative arts. Unfortunately, these unified standards did not become laws and remained internal instructions of the Administration. Also, the theory and practices that were elaborated by the *Central Restoration Institute* were not extended to all restorations of the nation's artefacts.

Nevertheless, since then, in Italy, articulated reflections on the criteria and methodologies of restoration and conservation have taken place, such as the *Theory Of Restoration* of Brandi (1963), focusing on issues of critical-aesthetic nature and respect for the authenticity of artefacts and the preservation of their original material. Successively, Giovanni Urbani's 1973 work extended the horizon of restoration also linking it to its environment and the conservation of the territory, and sought to develop the appropriate technical, scientific and organizational tools to enable the transition from restoration to planned conservation. His theories differentiated restoration, intended as an intervention on a single damaged work, from conservation as a broader activity aimed at preventing the degradation of the works. The programmed conservation proposal he formulated involved sig-

1 http://www.icr.beniculturali.it/home.cfm



nificantly increasing the role of non-invasive scientific investigations applied to artefacts, bringing a considerable cognitive contribution to restoration and laying the foundations for the contemporary conception of restoration and conservation interventions[2].

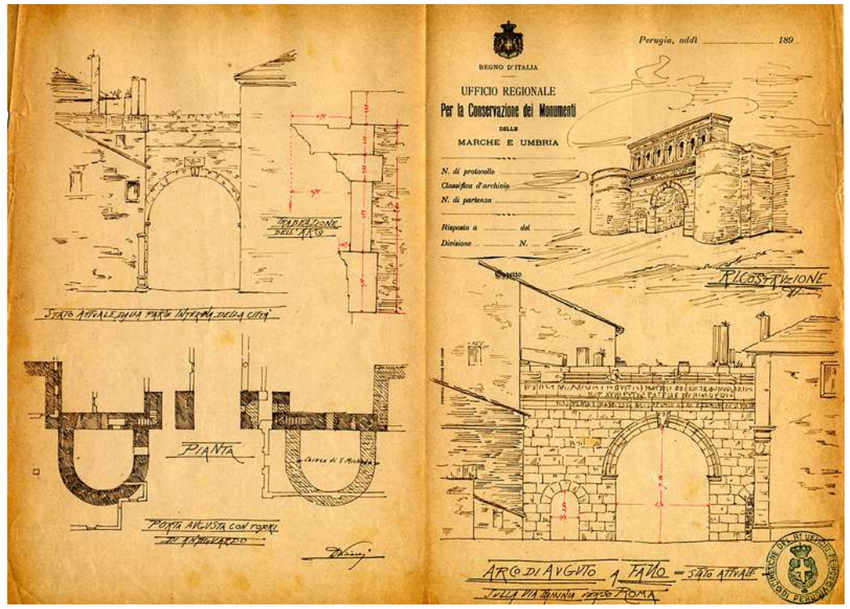



Figure 1.2
Example of photos and graphic surveys attached to the Conservation/ Tecnical Report. Source: *L'archivio storico delle schede di catalogo Ferrante F., Iulia S., Serafino T. Roma _12.11.2015.* http://www.iccd.beniculturali.it/index.php?it/153/archivio-schede-di-catalogo




Figure 1.3
Example of photos and graphic surveys attached to the Conservation/ Tecnical Report. Source: *L'archivio storico delle schede di catalogo Ferrante F., Iulia S., Serafino T. Roma _12.11.2015.* http://www.iccd.beniculturali.it/index.php?it/153/archivio-schede-di-catalogo

2 To date the ISCR operates the School of Higher Education, called SAF, referred to in Article 9 of Legislative Decree October 20, 1998, n. 368 and subsequent modifications. The SAF is responsible for the training of future restorers as reported in Legislative Decree 42 of 22 January 2004 "Code of cultural heritage and landscape".

## 1.1.2 Attempts at normalizing graphic language

A further step towards the elaboration of unified norms will follow the *Venice Charter* of 1964 to which Italian researchers such as Roberto Pane, Pietro Gazzola, and Cesare Brandi gave a fundamental contribution. The chart consists of 16 articles and summarizes the principles of the methodology of architectural restoration, unchanged today. Article 16 examines the importance of sharing the information gathered during documentation through the publications of the work carried out; this issue will later highlight the problem of how to normalize a common written and graphic language that is intelligible to all professionals in the field of conservation.

Over the years, national unification bodies, professional associations, user groups, industries, and scholars have developed numerous standards for digital architectural survey. These include the standards of the *International Standard Organization*-ISO/3567 [16], [17]; of the *Fort Worth District of the US Army Corp of Engineers* technical services [18], [19]; of the CADD Council, (promoted by the NIBS[3]), the national standard in the field of construction NCS [20]. Instead, in the field of conservation, and the community of restorers, the interest in products and the repeatability of practical operations prevail, and the methodological and technical aspect of documentation is underestimated.

Indeed, even today, the biggest problem of documentation and its subsequent cataloging is due to the process of normalization of historical conservation data, and the definition of the information acquired during the study and restoration of an artefact. For this purpose, in 1996, the UNI-NorMal Cultural Heritage Commission (regulations on stone material)[4] was set up, following a proposal presented by a group of researchers of the National Research Council (CNR) to define a unified methodology for the study of alterations of stone material and the evaluation of the effectiveness of conservative treatments on artefacts [21]. The purpose of the commission was to standardize, using the publication of recommendations,

3 http://www.nibs.org/ Il CADD Council today is called Facility Information Council (FIC).

4 The NorMaL Commission was created on the occasion of the "International Symposium on Conservation on Stone Materials" (Bologna 1977), promoted by the International Institute for Conservation (IIC). A group of researchers from the C.N.R. and I.C.R. presented a project entitled "Artistic Stone Works - A proposal for the Unification of the Methods of Studying Stone Decay and of Controlling Stone Conservation".



the methods of study, and control of the conservative interventions carried out on stone material, mainly architectural and sculptural. Among the documents produced and published by the commission, two directly concern the issues of graphic design: the NorMal 1/80 "*macroscopic alterations of stone materials, lexicon*," and the NorMal 17/84 "*metrological elements and dimensional characteristics: graphic determination.*"[22]. In particular, these recommendations are useful for graphic surveys because they build the basis for the modern graphic representation methods adopted in the conservation project, exceeding the limit of individuality and adopting a universal language, easily understood in every place, and by different operators. However, only some of these recommendations have become standard practice: this is the case of UNI 10924:2001, *"Cultural Heritage, mortars for building and decorative elements, Classification, and technical terminology: definition and description of mortars,"* and also UNI 10739:1998, "*Cultural Heritage, ceramic technology, terms and definitions*," drafted ex-novo by the Ceramics Group, while standardization of the graphic language for the documentation of metal artefacts, wood and painted canvas and boards, and paper material, has not yet been proposed. The only existing standards for the registration and documentation of these types of artefacts are those catalogs drawn up by the *Central Institute for Cataloguing and Documentation* - ICCD[5].

| ALTERAZIONI E DEGRADAZIONI | DESCRIZIONE | CAUSE | RIPRODUZIONE FOTOGRAFICA | RETINO |
|---|---|---|---|---|
| ***Macchia*** | *Alterazione che si manifesta con pigmentazione accidentale e localizzata della superficie; è correlata alla presenza di materiale estraneo al substrato (ruggine, sali di rame, sostanza organiche, vernici).* | - Biodeteriogeni;<br>- Ossidazione di elementi metallici (ferro, rame)<br>- Atti di vandalismo. |  |  |
| ***Mancanza*** | *Caduta e perdita di parti. Il termine si usa quando tale forma di degradazione non è descrivibile con altre voci del lessico.* | - Fenomeni di umidità ascendente;<br>- Perdite localizzate degli impianti di smaltimento e/o di convogliamento delle acque;<br>- Consistente presenza di formazioni saline;<br>- Soluzioni di continuità conseguenti alla presenza di fessurazioni e/o di lesioni strutturali;<br>- Soluzioni di continuità conseguenti agli stress termici in prossimità dell'innesto di elementi metallici;<br>- Errori di posa in opera e l'utilizzo di sabbie o malte poco idonee. |  |  |
| ***Patina*** | *Alterazione strettamente limitata a quelle modificazioni naturali della superficie dei materiali non collegabili a manifesti fenomeni di degradazione e percepibili come una variazione del colore originario del materiale. Nel caso di alterazioni indotte artificialmente si usa di preferenza il termine patina artificiale.* | |  |  |
| ***Patina biologica*** | *Strato sottile, morbido ed omogeneo, aderente alla superficie e di evidente natura biologica, di colore variabile, per lo più verde. La patina biologica è costituita prevalentemente da microrganismi cui possono aderire polvere, terriccio, ecc..* | - Azione di microrganismi autotrofi;<br>- Presenza di umidità o acqua;<br>- Caratteristiche morfologiche del substrato (scabrosità, asperità, rientranze, ecc.). |  |  |
| ***Pellicola*** | *Strato superficiale di sostanze coerenti fra loro ed estranee al materiale lapideo. Ha spessore molto ridotto e può distaccarsi dal substrato, che in genere si presenta integro.* | - Trattamento protettivo del materiale lapideo, a sua volta soggetto a degrado per ossidazione e contrazione in ragione delle sostanze impiegate. |  |  |

Figure 1.4
Alterations and degradation identified by "Normal-1/88 Recommendations. Macroscopic alterations of stone materials: lexicon" (CNR-ISCR, 1990, Rome). Degrade Abacus, page five.

5 http://www.iccd.beniculturali.it/it/standard-catalografici

An international stand characterizes the first "*Illustrated Glossary for the deterioration of stone material*" [23], published by ICOMOS (the International Council of Monuments and Sites), one of the three international non-governmental or intergovernmental organizations appointed to advise the UNESCO Committee in its deliberations. According to the 1972 UNESCO Convention[6], ICOMOS is the professional and scientific consultant for all aspects concerning Cultural Heritage and its conservation and is also responsible for the evaluation of all nominations for the *World Heritage List*. The group started its compilation task in 2001, summarizing seven documents[7] identified as the basis for the collection and combination of terms useful in a general glossary for the conservation and restoration of stone material. The resulting document includes translation of the terms into English and French with the corresponding definition; unlike the NorMal, the terms are accompanied only by illustrative photographs while a proposal of graphic representation is missing.

.....

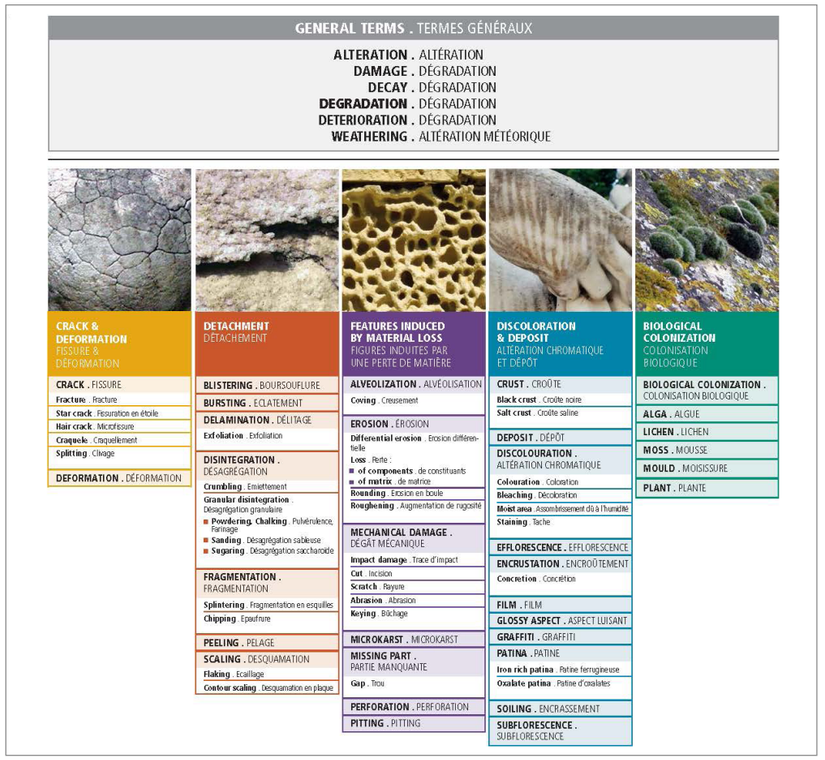
6 Convention of 1972 "Convention concerning the protection of the World Cultural and Natural Heritage" adopted by the General Conference at its sixteenth session, Paris, 16 November 1972.

7 (1) A. Arnold, D. Jeannette and K. Zenhder (1980), who performed that task within the framework of the ISCS petrography group activities; (2) 24 English terms with related definitions, published by Grimmer (1984) of the U.S. National Park Service; (3) Italian Standard Normal 1/88 published in 1990 and called "Alterazioni macroscopiche dei materiali lapidei: lessico"; (4) Terminology of stone decay forms on monuments, written by Jose Delgado Rodrigues from LNEC (Lisbon, Portugal); (5) B. Fitzner, K. Heinrichs & R. Kownatzki (1995), on classification and mapping of weathering forms, which was updated in 2002 by Fitzner & Heinrichs; (6) The seventh document (Franke et al. 1998) is a multi-authored book published as a deliverable of a FP5 European Commission research program. (7) The most recent document has been set up by a group of experts from Germany (VDI 3798. 1998) VDI stands for "Verein Deutscher Ingenieure, i.e. Association of German Engineers".






Figure 1.5
Illustrated Glossary for the deterioration of stone material, ICOMOS, and ISCS, "*Illustrated glossary on stone deterioration patterns.*"



Section 1.2

# The use of Software for creation and management of Documentation

As we have seen in section 1.1, since the late 1970s, following Giovanni Urbani's proposal regarding programmed preservation, the concept of restoration and conservation was extended from the single object to its environmental context, to assess the degree of conservation compatibility. This innovation led to the need to identify a software application for managing documentation for the knowledge acquisition and the planning aims not only for individual objects but also for the set of environmental and territorial entities.

## 1.2.1 Geographic information systems for overall spatial data management

An essential step towards documentation management was the adoption of geography software, as it was understood that the problems related to the statistical analysis of satellite images and the creation of cartographic documents were similar to the problems of documentation for cultural heritage. In fact, Geographic Information Systems (GISs) integrate analysis on the relationships between the object of interest and the surrounding environment, including predictive models to simulate the evolution of phenomena observed or expected to act on the object, based on physical data such as humidity, temperature, air flow [24],[25]. For these reasons, several *Information Systems* have been developed in Italy for the general management of information relating to the cultural heritage existing in the national territory. The Ministry of Cultural Heritage and Activities currently has three systems for managing spatial and cultural data:

***General Information System of the Catalogue*** **(SIGEC)**[8], created by the *Central Institute for Catalogue and Documentation* (ICCD), is a web-based platform that manages the entire Cultural Heritage cataloguing flow with the digitization of ICCD Reports. The system includes data relating to different types of heritage (archaeological, architectural and landscape, demo-ethno-anthropological, photographic, musical, naturalistic, numismatic, scientific and technological, historical and artistic) usually covered by different administrative areas of competence, and therefore previously partially and unevenly classified [26],[27].

***Environmental and Landscape Territorial Information System*** **(SITAP)**[9], created by the *Directorate-General for Architectural and Landscape Heritage* (DGBAP), is a database for the protection of landscape heritage which lists, with geographical reference on a national scale, all areas subject to landscape protection measures declared to be of considerable public interest. The system contains data related to basic map information, such as administrative limits of Regions, Provinces, and Municipalities, etcetera. Concerning landscape heritage, the database contains information relating to elements protected as "natural beauty" (according to Law No. 1497/39, now art. 136 of Legislative Decree 42/04, Code of Cultural Heritage and Landscape); areas of respect for rivers, lakes, coasts (protected by Law No. 431/85, today art. 142 of the Code of Cultural Heritage and Landscape), parks and nature reserves, forests, mountain areas, glaciers, volcanic zones and other areas under protection; areas of archaeological interest.

***Information System of the Cultural Heritage Risk Map*** **(CDR)** [10], developed in the 1990s by the Central Institute for Restoration (ISCR), it is the data management system for the state of preservation of the entire national heritage. This information system is a working tool to rapidly identify, within the Italian heritage, which are the assets most exposed to the risk of degradation and/or loss, so as to plan interventions to be carried out with greater urgency. With the aid of statistics, the Risk Map System connects the archive of information on individual monuments to the territory in which they are located, because the risk of damage does not depend only on artifacts' preservation conditions, but it is related to the charac-

8 http://www.iccd.beniculturali.it/it/sigec-web

9 http://www.sitap.beniculturali.it/

10 http://www.cartadelrischio.it/

teristics of a territory and the risks that it presents; as is evident, for example, in the case of natural disasters. Risk assessment *R* is calculated in consideration of two different data: danger factor *P*, indicating the presence or likelihood of damaging events depending on territorial location, and vulnerability factor *V*, as in the likelihood of an artefact to be damaged, in relation to its preservation conditions [28],[29],[30],[31].

Figure 1.6
*Website page of SITAP.*

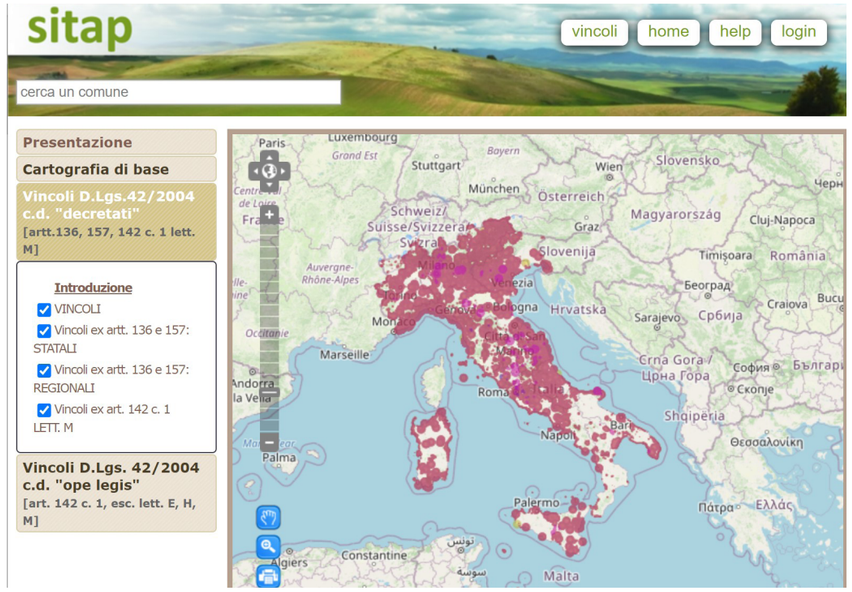
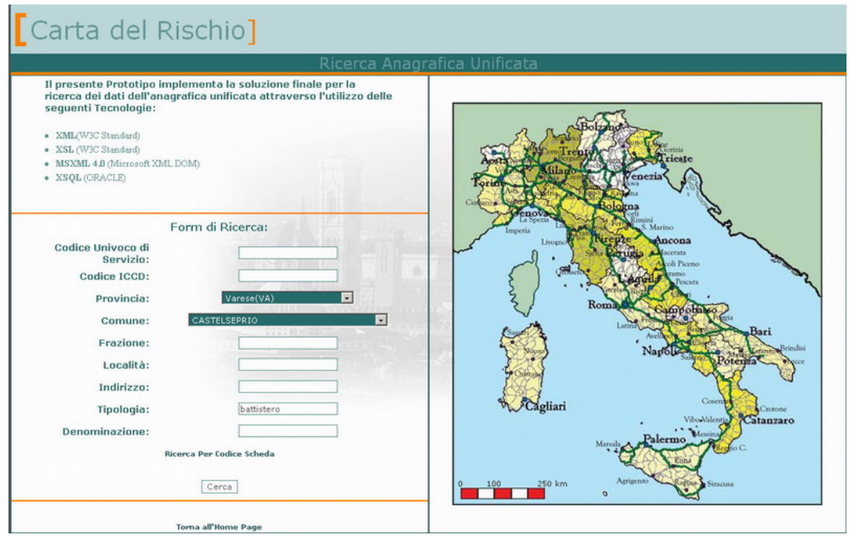



Figure 1.7
*Website page of Risk Map.*






## 1.2.2 The use of software for the creation and management of Thematic Maps

In the Geographic Informative Systems listed, historical monuments are considered as "specific entities," that is, it is not possible to connect the information with their morphological characteristics. Conversely, the graphic documentation of the artifacts preservation conditions, recorded in *Thematic Maps*, is performed on a more detailed scale, that considers the complexity of their morphology and constituent elements. Therefore, *Thematic Maps* can be considered as an extension of the Cultural Heritage Risk Charter because it constitutes an analytical deepening of specific data that is not taken into consideration by the information system, which instead manages spatial data at a general level

### 1.2.2.1 CAD softwar

Thematic Maps mainly executed with manual drawing, began to be supported by computers in the early 1950s when the importance of digitalizing information led to a progressive abandonment of hand drawing and the development of computer-aided drafting (CAD) systems[11]. Initially, these tools were developed for the construction and mechanical sector but, at the end of the 70s with the rapid progress of technological science, the first systems accessible to a large group of users were designed, culminating in the commercial launch of Autocad 1.0 on December 1982 [12]. CAD was thus borrowed from the engineering sector and progressively adapted to the documentation needs of restoration of all types of artefacts [32],[33].

CAD in the field of restoration is mainly used for two-dimensional representations in vector form of objects through elevations, sections, plants, and profiles. Compared to other graphic drawing software, it allows the performance of precise analysis and quantitative measurements between the drawing areas (such as length of cracks, overall areas of saline efflorescence, etcetera). This feature has made them indispensable for the design of restoration interventions, especially in the architectural field. In fact, the numerous architectural surveys of monu-

11 The Lincoln Labs and the Whirlwind Group for MIT and U.S. Army were the first developers

12 The result of a work undertaken in 1978 by Michael Ridde and continued by John Walker.

ments of historical interest performed in CAD to this day represent the body of accessible and widely present geometric data in the institutional archives. For this reason, they are often used as a basis for obtaining 3D digital models of historic buildings and virtual reality tour development [34],[35],[36].

In all CAD systems, the data is structured hierarchically with the layering system: each geometric primitive of a drawing is assigned to a single layer which can contain many graphic entities, but each one only belongs to one layer; this allows the design to be well organized and manipulated

### 1.2.2.2 GIS Software

Documentation is, however, characterized by different types of files such as graphs, texts, photos, reports, and tables that cannot be managed, analyzed, and stored correctly using CAD. Moreover, quantitative executable analyses are limited and exclude many useful data analysis operations. For these reasons, the efficiency of executable drawings with CAD and the potential for data analysis and file management of GIS has been combined into a hybrid software since 1996 [37] and to date, all GIS software communicates with CAD and has implemented all the design functions.

The use of GIS technology offers a decisive contribution to the documentation problem because it allows some relationships between fundamental data, such as the topological relationship between a data archive and a graphical representation, and a strong relationship between raster and vector graphics. Compared to CAD, GIS systems integrate various types of files such as those containing vector data; raster data (cartography and images); alphanumeric data (attributes of graphic objects organized in tables in the database), texts, tables, spreadsheets, graphics, movies, 3D models, and allow to export and share projects on the web.

In addition to the variety of reading and production of different types of files, GIS also allows complex processing on them: quantitative, statistics, modeling, predictions. The data can be consulted through simple selection tools directly on the graphic drawing or through specific queries in the data archive, searching for individual keywords or through SQL language (*Structured Query Language*).

The following are some examples of possible spatial queries and operations, in order of increasing complexity:



Where is object A?

Where is A in relation to object B?

How many occurrences of A are within distance D of (or contained by) B?

- Which objects intersect this line?
- Which objects are in a specified position with respect to this line?
- Which objects are at a certain distance from others with a specific combination of attributes?
- Possibility of creating new objects from existing data.
- Display data based on parameters selected.

In addition, GIS offers the possibility to model spatial phenomena, simulating a process's effect over time for a given scenario (predictive modeling).

All projects can be exported through interactive systems that can be used on the web: web-gis. These functionalities can convey the geographic information contained in the database of a server through user-friendly interfaces.

The numerous topics mentioned respond to immediate needs and have been the subject of numerous studies in recent and past years that have led to the formalization of methodologies and their implementation to the entire GIS applications in functionality (tools).

The first development of geographic information systems dedicated to the interaction between graphic documentation and databases have been used to document archaeological sites and relate the finds to their context [38],[39].

In 1999, the first experiences of metrical and spatial analysis of mural paintings were performed using CAD and GIS systems. These were documented in a relevant conference proceeding entitled "GraDoc" (*Graphic Documentation Systems in Mural Painting Conservation*), which collects and illustrates important application projects in this field [40].

In Italy, significant practical applications have been executed in the field of architectural restoration, including:

the proposal of "a computerized recording of the state of conservation of monumental interest surfaces" realized for the cloister of S. Chiara in Naples and the Servian walls in Rome. In this project, an archive of preservation status data is directly associated with a graphical basis, that is to say, the synthetic representation of study objects [41].

The “proposal of a survey management system” for the facade of S. Maria del Giglio in Venice, for which an informative geographic system called SIR (Informative System Restoration) was created [42].

The “GIS of restorations” experimented by the Physics laboratory of the Higher Institute for Conservation and Restoration for the Crypt of San Magno in the cathedral of Anagni. This system records information on the preservation conditions of the frescoes, the location and type of damage suffered, diagnostic investigations, micro-climatic measurements, and restorations performed [43].

The ARTPAST[13] project (“Web application for the protection and enhancement of Cultural Heritage in underused areas”) started in 2005 within the Ministry of Cultural Heritage and Activities, that addressed the problem of structuring and computerizing restoration documentation [44]. Two different software applications developed by the Superintendence of Pisa have been proposed for the ARTIPAST project:

ARISTOS, a web IT archive dedicated to the organization and management of information related to the history of protection contained in the archives of the Superintendence;

SICAR, a web-GIS which allows to visualize high-resolution photographic images and to superimpose on them degradation and interventions maps [45].

### 1.2.2.3 The SICAR Software

Currently, in Italy, SICAR[14] is the only software system to have obtained a formal recognition from the Ministry for Cultural Activities and Tourism that, in 2012, officially adopted it as a shared IT platform for the executive design and documentation management of restoration sites.  The aim is now to interface it with the other recognized cataloguing systems, which are the general informative catalog System SIGeC- ICCD and the territorial Risk Card System (CDR) [46],[47]. SICaR is a software which allows to manage time and cost estimates, historical and technical-scientific documentation, the maintenance and monitoring of cultural heritage. For this reason, the system has been adopted by numerous superintendents for the plan and documentation of the restoration of historic buildings. The SICaR

13 http://www.artpast.iccd.beniculturali.it/index.php?id=1

14 http://sicar.beniculturali.it:8080



prototype was developed in 2003 by the Superintendence for Architectural, Landscape, Historical, Artistic and Ethno-Anthropological Heritage (BAPSAE) of Pisa and Livorno, and is the result of research activity to manage the documentation of the restoration performed on the stone surfaces of the Tower of Pisa, conducted by the Central Restoration Institute and the Computer Research Centre for Cultural Heritage of the Scuola Normale Superiore di Pisa. In that case, the complexity of the work made it necessary to manage a considerable amount of data (materials, types of degradation, investigations, and interventions performed), and a specific GIS was created for this purpose, the AKIRA GIS Server. The particular morphology of the artefact highlighted the difficulty in using two-dimensional graphic references, requiring the tower to be broken down into a series of architectural elements.

As part of a doctoral thesis [48], the University of Pisa began an experiment based on a general national and international survey of existing information systems and projects focused on an analysis of the ministerial Sicar-Online Information System for the documentation of Restoration Sites[15]. A five-year agreement was then stipulated between the Ministry of Cultural Heritage and Activities and Tourism (MiBACT)), the Vatican Museums, and the University of Pisa, thanks to which a project was set up within SICaR w/b to organize the data relating to a sarcophagus preserved in the Vatican Museums. This project optimized the existing system by making it more useful for documentation, management, and the consultation of information relating to ancient polychromies and scientific analysis. [49].

Since 2008, other national projects promoted by MiBAC have allowed the training of staff and the release of other modules for the optimization of Sicar w/b. In addition, together with the Central Restoration Institute and the Opificio delle Pietre Dure in Florence, the lexicon relating to degradation and interventions has been normalized, recognizing the absolute need to maintain a common language to allow the exchange of information.

15 http://vcg.isti.cnr.it/~siotto/thesis/index.html

Figure 1.8
Screenshot of AKIRA GIS server, information system for the documentation of the Tower of Pisa. The image shows the documentation of the interventions made on a sector of the tower. Source: Bartolomucci, C. 2008. “Nuovi Metodi per La Documentazione.” In Trattato Di Restauro Architettonico. Grandi Temi Di Restauro. Vol.X, ed. Giovanni Carbonara. Torino: UTET SCIENZE E TECNICHE, 105–40.

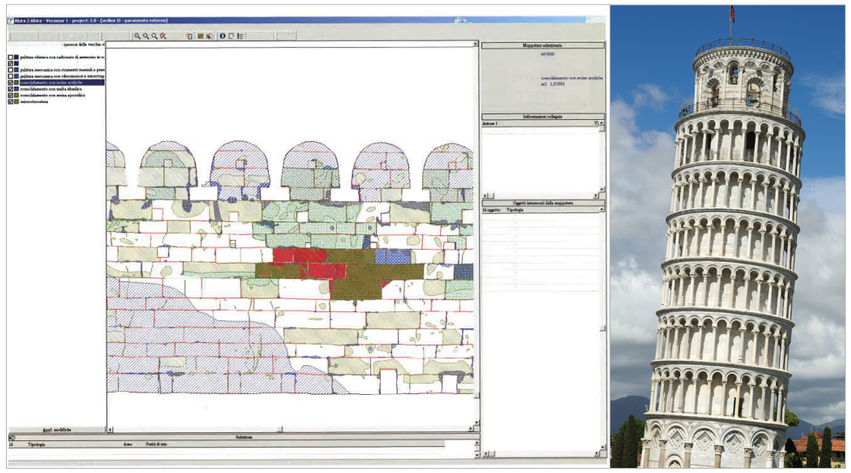
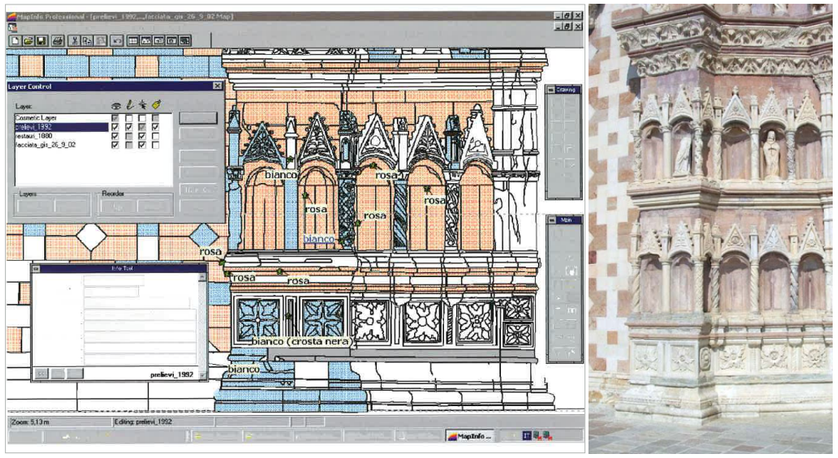


Figure 1.9
Screenshot of AKIRA GIS server, information system for the documentation of the Church of Santa Maria di Collemaggio, L'Aquila. Source: Bartolomucci, C. 2008. “Nuovi Metodi per La Documentazione.” In Trattato Di Restauro Architettonico. Grandi Temi Di Restauro. Vol.X, ed. Giovanni Carbonara. Torino: UTET SCIENZE E TECNICHE, 105–40.





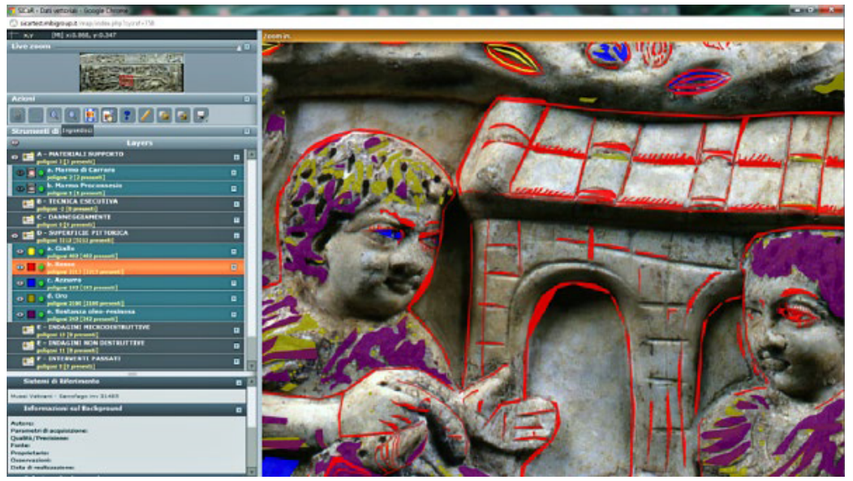



Figure 1.10
Screenshot of Sicar in “map” mode: details of the color and overlay of the layers corresponding to the different colors, gold, and oil-resinous substances. Source: Siotto, E., Scopigno, R., Baracchini, C., & Santamaria, U. (2016). Sperimentazione del sistema ministeriale SICaR w/b per la gestione e la consultazione informatizzata dei dati sulla policromia. Archeologia e Calcolatori., 27, 131-151.

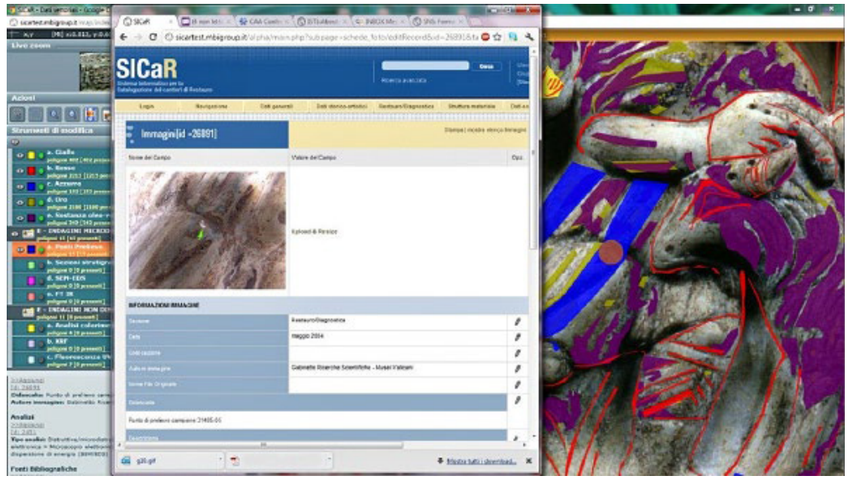



Figure 1.11
Screenshot of Sicar: an “Image Card” is also associated with the sampling point which shows magnification of the point in which the micro-sampling was carried out. Source: *Siotto, E., Scopigno, R., Baracchini, C., & Santamaria, U. (2016). Sperimentazione del sistema ministeriale SICaR w/b per la gestione e la consultazione informatizzata dei dati sulla policromia. Archeologia e Calcolatori.,27, 131-*

## Section 1.3 Diagnostic Imaging

This second research topic concerns a significant aspect of documentation: diagnostic investigations.

Restoration is today universally understood as a conservative intervention that must necessarily start from an in-depth knowledge of an artifact. Because of its material aspect, the disciplines of chemistry, physics, and related ones offer prove considerably useful in understanding its nature and in preserving its original expressive content. Artistic Diagnostics is thus intended as the set of scientific investigations that can provide information on the execution technique and the preservation conditions of an artifact that may be otherwise unobtainable. The complexity and relevance of diagnostic investigations depend on the fact that the materials present in artifacts are only partially the original ones used by the author, each artifact being subject to significant changes due to various factors such as the natural aging of its materials, degradation pathology, incorrect restoration work or *pentimenti* that may have introduced new materials and chemicals. This is why any analytical technique that detects what is not directly visible or perceptible is an essential means of diagnostic investigation.

Chemical research was the first technique to allow investigation of an artifact's constituent materials and their degradation, but the decisive step was made with the development of the principal diagnostic imaging techniques.

Current imaging techniques use digital photography to record optical phenomena due to radiation reflected, transmitted, or emitted in raster images when the material is illuminated with visible light. New techniques allow an object to be observed using wavelength ranges in the electromagnetic spectrum, that include and extend beyond the possibilities of the human eye. These have had a wide diffusion in the field of cultural heritage as they are able to provide a preliminary understanding of an artifact and indicate the choice of possible micro-sampling points. Therefore, they can guide restorers in adopting an appropriate type of intervention and plan a system to control the preservation conditions of an artefact. The versatility of these techniques makes it possible to repeat the investigation frequently over time, allowing the progress of the conservation intervention to be monitored, and identify any variations in the post-conservation.

The methodology proposed in this thesis focuses primarily on a statistical analysis of these images, since more than others, it highlights the features sought by the conservator and art historian, representing a cross-boundary terrain that unites art history and scientific culture.

In brief, the aims pursued by diagnostic methodologies can be divided into three groups:

***1. Acquisition of historical, artistic, and technical knowledge about the artifact:*** Analysis of constituent materials and execution techniques; dating and authentication based on stylistic and scientific observation.

***2. Ascertaining problems related to restoration:*** Assessment of the preservation conditions and degradation problems of an artifact (material/environmental interaction); Recognition of any previous restoration work (in principle, to be removed using the most suitable methods); Choice of materials to be used for the new restoration intervention through constant monitoring of possible interactions with the original materials.

***3. Recognition and management of environmental conditions in the artifact's destination place:*** the degradation of each material is strongly influenced by the environmental conditions of the place where it is located; a chemical-physical analysis can provide elements of evaluation and suggest solutions for the correct balancing of conditions such as humidity, temperature, etc. for the ideal preservation of the artifact.

## 1.3.1 Historical background

This paragraph describes the first applications of photographic techniques, which represented a technological connection between the knowledge of specialists (chemists, physicists, doctors, art historians, criminologists) and the new discipline of artistic diagnostics.

Artistic diagnostics as a discipline was born from the relationship between science and art which, after its first steps in the Renaissance, was consolidated during The Enlightenment. The chronological reconstruction of its historical development is difficult for several reasons, among which, the fragmentary nature of the available data being the major cause. In fact, it has been a path characterized since its inception by influences from heterogeneous cultural fields and by the commitment of different institutions of international scope through which it became possible to facilitate the work of researchers.

### 1.3.1.1 Macrophotography and diagnostics in visible light

The common goal of this line of research was the development of a method of observation that would go beyond the limits of the human eye and make it possible to examine an artifact in its smallest details and within its structure, proceeding beyond simple autoptic observation. This need was met at the end of the 18th and beginning of the 19th century with the development of two optical instruments capable of magnifying small portions of a painted surface: the *megascope* and the *megagraph* (or tracing microscope) [1] [50].

The first applications of photographic diagnostics took place in the visible spectrum, particularly through the execution of macro-photographs, micro-photographs, and photographs in raking light [2] used to observe chemical reactions between the constituent elements of materials.

1 The megascope was invented by physicist J.A.Charles in 1780. Through a combination of lenses it projected the enlarged image of objects, allowing a visual analysis of surface details. A few decades later, in 1822, this instrument was adapted by Charles Chevallier for the creation of the tracing microscope or megascope. Above the eyepiece of the microscope it contained a piece of frosted glass, adjustable in height, on which the image was focused. This was the forerunner of modern photographic magnifiers.

2 These two techniques will be developed in paragraph 2.3. Walter Gräff, a museum curator and art historian, speaks of these techniques. Since 1910 he used them to study the material and stylistic characteristics of the paintings preserved in the Alte Pinakothek in Munich, identifying non-authentic parts or those resulting from restoration.



The Scottish chemist Arthur Pillans Laurie played a fundamental role in the application of macro photography. He developed an instrument similar to the megagraph with which he analyzed the artists' brushstrokes, which he considered a characteristic element for recognizing the actions of specific painters [51]. In the cultural heritage field, microphotography developed in parallel with the evolution of microscopy, making it possible to document the characteristics of pigments. These were analyses aimed at the recognition of pigments through optical examination and microanalysis, through the observation of some reactions of samples coming into contact with particular substances[3][52],[53],[54],[55],[56],[57],[58],[59]. This analysis tool helped the chemist Max Von Pettenkofer to discover that the relationships between the oily components of paintings on canvas and variations in temperature were the main cause of their deterioration. Thanks to this discovery, he developed his method for microclimatic control in museums and the cleaning of paintings with solvents. His method, called the "Pettenkofer method," was widely spread in Italy; Giovanni Secco Suardo talked about it in his first Italian scientific restoration handbook [60].

### 1.3.1.2 Photography and electromagnetic radiation: X-rays and Ultraviolet Fluorescence.

Concerning physics-related methodologies, the first experiments in the field of cultural heritage were conducted in that part of the electromagnetic spectrum not directly perceivable by the human eye, particularly X-rays. The first studies date back to 1896 when the physicist Wilhelm Conrad Röntgen accidentally discovered X-rays while experimenting with cathode ray tubes. He observed that ra-

3 The first empirical, and then 'scientific', attempts were based on chemical analysis and applied to materials and objects of mainly archaeological interest. In 1796 the German chemist Martin Heinrich Klaproth published the first results of his analytical method to determine the physical-chemical structure of coins minted in the Greek-Roman period. The first publications on the analysis and identification of painting material and support date back to the early years of the xix century; the studies dealt mainly with pigments and inert materials on encaustic wall paintings found in Pompeii. The recognition of the pigments took place through chemical investigations carried out on small quantities of samples. The chemical analysis conducted on the samples emphasized that a painting represented not a surface but a stratigraphic structure, stimulating new methods of physical-optical investigation, such as X-rays and infrared photography. For the diagnostic sector, an outstanding achievement was the introduction, between 1945 and 1955, of dating through the radiocarbon (14C method). This system completely changed the historical-artistic methods that had been used until then to date organic artifacts, finally giving an absolute scientifically proven certainty.

diation of a mysterious nature was able to pass through solid objects was emitted from the anode of such tubes and impressed photographic plates located behind them[4]. In the artistic field, the first applications were carried out to study lead pigments in paintings and to detect fakes[5] [61],[62]. Other fundamental contributions were given by the German scientist Alexander Eibner, who started pioneering work on the use of the ultraviolet lamp in the study of fluorescence in ancient paintings[6] [63], [64], [65]. The use of ultraviolet sources in the investigation of works of art was established in 1921, when the American physicist Robert William Wood announced that he had patented a glass filter based on nickel oxide capable of stopping visible radiation and transmitting ultraviolet radiation with wavelengths between 330 and 380 nm, particularly suitable in exciting fluorescence of materials. The phenomenon of ultraviolet fluorescence emitted by "Wood's Lamp" was studied and codified by many researchers, with many volumes being published on the cataloging of materials' different responses, particularly referring to the organic binders of pigments.

### 1.3.1.3 Infrared photography

The first experiments in black and white infrared (IR) photography date from 1930, although William Herschel had discovered radiation in 1800. [66]. The delay in the use of infrared compared to ultraviolet and X-rays is due to the fact that the substances capable of sensitizing the silver halide granules contained in the photographic film were discovered only in 1873 and 1905. These substances allowed the recording of spectral responses up to 900 nm [67]. Between 1925 and 1932, other substances were identified, obtaining IR registration even up to 1300 nm. [68]. Infrared rays have a considerable capacity to penetrate through the atmosphere due to their longer wavelengths. For this reason, this technique saw a massive development in the field of aerial photography, for military and topographic uses. Pioneering research in the artistic field took place within the *Fogg Art Museum* in Havard and at the *Laboratoire of the Louvre* and was aimed at sampling the spectral responses of some modern pigments [69], [70], [71]. The

4 For these studies Röntgen received the Nobel Prize for physics in 1901.

5 Between 1924 and 1926 the Pinakothek in Munich, the Louvre Museum, the Fogg Art Museum and the National Museum of Naples acquired or used X-ray equipment.

6 The discovery of the existence of infrared and ultraviolet radiation dates back to 1800 by Frederik William Herschel and to 1803, by William Hyde Wollaston, respectively.



first systematic researches studying painters' techniques through IR photography, capable of revealing the drawing and details in the preparation of canvases and painted panels, were published from the 1950s [72].

### 1.3.1.4 Infrared Reflectography

In 1960 the Dutch physicist Johan Rudolph Justus Van Asperen De Boer perfected *reflectography*, a system that allows to penetrate beyond materials which in photographic infrared hide the legibility of underlying layers. The first instruments, called reflectograms, date back to 1966, operating in the band of the electromagnetic spectrum up to 2000 nm, a wavelength value Van Asperen established as optimal. The methodology he elaborated was based on Kubelka Munk's theory, applied to the processes of diffusion and absorption of pigments in the region of infrared radiation [73]. Reflectography proved useful for the study of preparatory drawings and pictorial reconsiderations. The first trials were conducted on Van Eyck 's polyptych of the Mystic Lamb and several works in Amsterdam's Rijksmuseum. Then, in 1960 Kodak patented the Infrared Aero 8443, fake color films which allowed to visualize responses of pigments not detectable in visible light [74]. This was first tested at the *Opificio delle Pietre Dure* in Florence in 1978. Model tablets were photographed with different preparations, on which pigments with different binders had been spread. The test proved useful in providing information on the type of pigments used [75]. In more recent years, technological advancement has allowed digital acquisition of reflectographic images and the possibility of assembling details using HD photography.

### 1.3.1.5 Thermal Infrared

After the Second World War, technological experimentation resumed and new methodologies centered on infrared rays and thermal waves were introduced. The first thermal scanning instrument, sensitive to a 700-1300 nm band, was created in1953, allowing for the first thermal infrared images to be obtained [76]. Later, the aim became to increase devices' sensitivity, obtaining acquisitions from 1500 up to 5600 nm. The first images were grayscale, and the different tones represented different degrees of temperature. In 1973 Giovanni Urbani [7] presented the results of one of the first experiments in thermography in the field of cultural

7 The future director of the Central Institute for Restoration.

heritage. He recognized the ability of this technique to highlight the degenerative phenomena of architectural structures, such as lesions, detachments and infiltration [77].

### 1.3.1.6 Official introduction of Artistic Diagnostics: international cooperation and scientific laboratories

Collaborations between scientists and art historians [78] led to the creation of numerous scientific laboratories in the most important museums of the world[8]. An immediate consequence was the evolution of specialized literature with more authoritative and numerous publications[9][79].

In the 1930s, the pioneering phase of the new discipline ended. The term *artistic diagnostics* was consciously and officially used for the first time during the International Conference for the Study of Scientific Methods Applied to the Examination and Preservation of Paintings, held in Rome from 13 to 17 October 1930. The Conference, organized by the *Office International des Musées* (OIM), was the beginning of the process of international methodological standardization of scientific analysis and favored the creation of modern museums' scientific laboratories [80]. The importance of scientific investigations was also confirmed in the Restoration Charters, specifically in the Athens Charter of 1931, recommending that conservators and architects in every country should collaborate with representatives of the physical, chemical, and natural sciences in order to obtain reliable results for their increasing application. From 1950 onwards, several international committees were established to promote cooperation between museums, the most important of which are the ICOM (*International Council of Museums*) and the IIC (International Institute of Conservation of Historic and Artistic Works) based at the National Gallery in London and the ICCROM (*International Center for*

8 In the museum area, among the most active pioneer centers we can mention: the University of Munich with its "Research Institute for Painting Technique" (versuchsanstalt für maltechnik); in 1918 the diagnostic laboratory at the restoration laboratories in Moscow and in 1919 the British Museum Research Laboratory, which established itself as the most important institute of scientific research applied to archaeological finds. In 1925 the Fogg Art Museum of Harvard University, in 1927 the Museum of Fine Art in Boston, in 1930 the Metropolitan Museum of Art in New York, in 1938 the Doerner Institute in Munich.

9 In particular, we can mention the articles published in the magazine "Mouseion", established by the office international des Musées, whose legacy was collected from 1948 by the magazine "Museum" edited by UNESCO, available in digital version. https://unesdoc.unesco.org/ark:/48223/pf000010304 .



*the Study of Preservation and Restoration of Cultural Property*) based in Rome. Divulgation of the studies was assigned mainly to three journals: "Studies in Conservation," "IIC Abstract," "IIC News." In this period, new scientific laboratories were opened in Italy and Spain, aiming also at the professional training of conservators and restorers.

In Italy, a significant contribution to the scientific evolution of conservation was made by researchers in national institutions, such as the Central Institute of Restoration in Rome and the National Research Council (CNR) in Rome and Milan. From 1924, the first diagnostic experiences in the *restoration cabinets* and scientific laboratories of the Superintendencies of Florence, Rome (and the Vatican Museums and Naples) began. Diagnostics became the basic working system for the Istituto Superiore per la Conservazione e il Restauro (ISCR), which since its beginnings had adopted interdisciplinarity as the foundation of correct and precise restoration practice. It in fact employs art historians, architects, archaeologists, physicists, experts in environment control, chemists, biologists as well as conservator/restorers specialized in different types of materials of historical and cultural interest such as paintings, textiles, works on paper, metal, ceramics, stone, leather and wood, to name a few.

## 1.3.2 Typologies of diagnostic investigations

In the first instance, it is essential to classify chemical-physical methodologies into two classes; invasive and non-invasive.

***By invasive analysis,*** we define those which in some way alter the artifact or a part of it because they involve a material modification such as taking a micro-sample, for example, which can be used for a single examination and then destroyed. Invasive analysis can entail:

- a variation in the chemical or physical structure of an artifact
- the creation of a cavity for internal inspection,
- the introduction of foreign materials,
- the breaking of chemical binders and the production of different molecules from the original ones.

***Non-invasive analysis*** refers to that which induces no alteration to the object. This type of analysis can be used on fragments or micro-samples, guaranteeing the non-destruction of the same. Non-invasive analyses can be further divided into two groups, based on the size of the examined area:

- Imaging techniques group diagnostic investigations that are performed on more or less extensive areas that give an image of the surface or volume under examination. These analyses use electromagnetic energies exploiting different materials and pigments responses to different forms of electromagnetic radiation. These techniques reflect the characteristics of the materials in the images, highlighting them in areas or points which differ by brightness or color. Photographic diagnostic techniques will be described in paragraph 2.3.
- Local or spot-on methodologies investigate small areas of the order of a few mm2. They are generally spectroscopic, i.e., providing information related to wavelengths or radiation energies of particles according to specific techniques. The characterization of the constituent materials is, in this case, expressed in a graph that relates to the physical processes that take place in the area of interest

The wavelength range used for heritage diagnostics varies from around 350 nm to 1700 nm. Outside the sensitivity range of the human eye, at wavelengths greater than 780 nm we encounter infrared, followed by microwaves and radio waves. Wavelengths shorter than 380 nm pertain to the regions of ultraviolet and then X-rays and gamma rays.

A generic configuration for multispectral imaging consists of three main components:

1) Incoming radiation, generated by a source and striking the target object;

2) The object interacting with the radiation received;

3) Outgoing radiation, which results from the interaction between the incoming radiation and the object and moves from the object to the recording device.

Both incoming and outgoing radiation are usually in one of the three ranges displayed in figure 1.12: ultraviolet radiation (UV 200-400nm), visible light (VIS 400-700nm), or infrared radiation (IR 760-40000 nm).



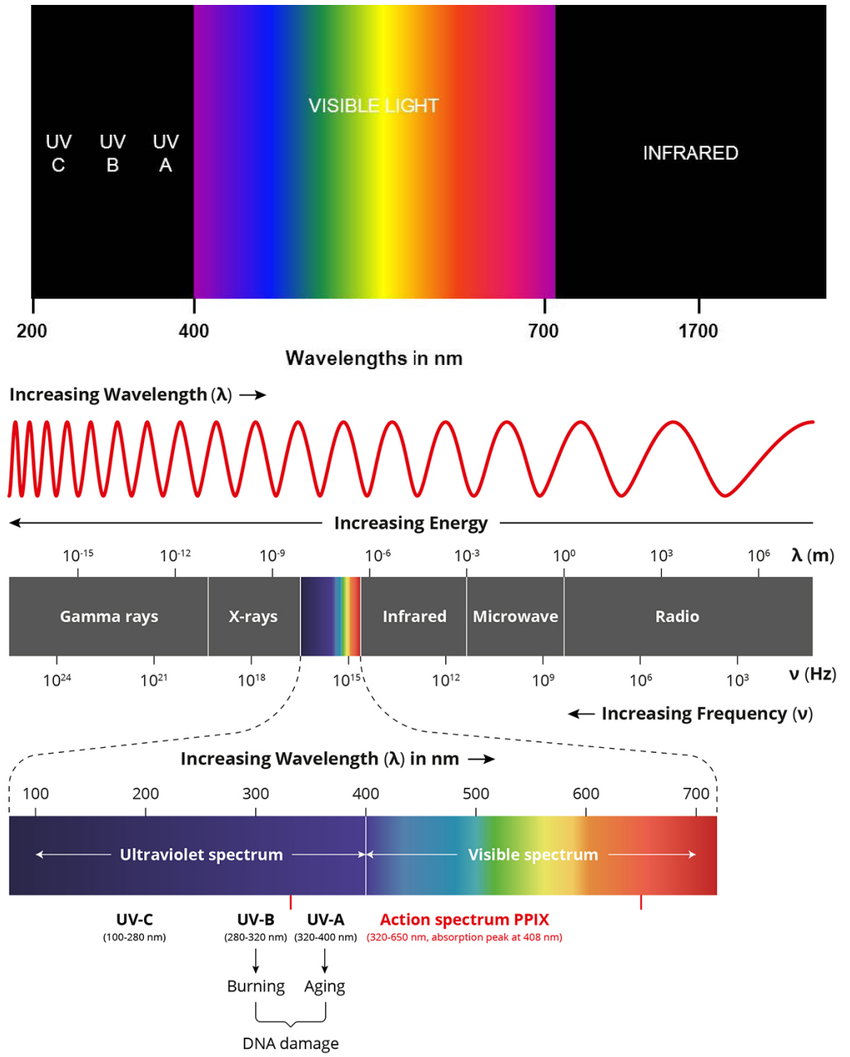



Figure 1.12
Wavelength ranges in the electromagnetic spectrum commonly used for multi-spectral imaging in cultural heritage applications.

The extent to which radiations penetrate the object depends on the wavelength, and on absorbency of the materials of which object is made; wider wavelengths generally penetrate deeper.

The radiation arriving at a particular point in the object can be:

*(i)* absorbed;

*(ii)* reflected; and/or;

*(iii)* absorbed and re-emitted as luminescence at longer wavelengths.

Each result produces a set of images that provide specific information for that point. Therefore, by selecting particular combinations of lighting and sensing fields, you can obtain information about the distribution of materials.

Multispectral imaging techniques require the use of a radiation source and a receptor capable of recording its effects on artifacts and making them perceptible to the human eye [81]. Most of the information to be transcribed in such graphic documentation comes mainly from these techniques. Characteristics related to the nature and condition of the artifacts are highlighted by areas or points that differ in resulting brightness or color [82].

Multispectral imaging is used before, during, and after an intervention in order to create photographic documentation that will become an integral part of the historiography of an artifact and a potential continuous source of information even after the restoration is completed.

Images thus produced therefore fall in two categories:

***Reflected radiation images:*** the wavelength range of the incoming and outgoing radiation is the same.

***Emitted radiation or photo-induced luminescence images:*** the range of wavelengths of incoming and outgoing radiation differ. According to the physical rules governing these phenomena, the output radiation is less energetic than the incoming radiation. The incoming radiation is called “excitation,” while the outgoing radiation is called “emission”.

It is also possible to further divide these categories into two groups:

***Images obtained in the field of visible light***
***Images obtained in the field of non-visible radiation.***

Below is a table with the main photographic diagnostic techniques used in the field of cultural heritage.



| REFLECTED RADIATION IMAGES | VISIBLE | NON-VISIBLE |
|---|---|---|
| Visible-reflected (VIS) images | X | |
| Infrared-reflected (IRR) images | | X |
| Ultraviolet-reflected (UVR) images | | X |
| False-color reflected images | X | X |
| Ultraviolet-reflected false-color (UVRFC) images | X | X |
| Infrared-reflected false-color (IRRFC) | X | X |
| EMITTED RADIATION OR PHOTO-INDUCED LUMINESCENCE IMAGES | VISIBLE | NON-VISIBLE |
| Ultraviolet-induced luminescence (UVL) images | X | |
| Visible-induced infrared luminescence (VIL) images | X | X |
| Visible-induced visible luminescence (VIVL) images | X | X |

Table 1.1
Classification of the two categories (reflected radiation and emitted radiation/luminescence images) in the visible and the non-visible light spectra.

The following paragraphs will only describe the multispectral techniques examined for artifact studies to which the aforementioned methodologies have been applied.

### 1.3.2.1 Visible-reflected (VIS) - Reflected radiation images

The human eye can only perceive radiation of wavelengths between 400 and 780 nm. Within this band, wavelengths of between 380 and 430 nm are perceived as violet light, those from 430 to 490 nm as blue, those from 490 to 560 nm as green and those between 620 and 700 nm are identified as red.

Photographic images taken in the field of visible radiation can be defined as diagnostic because they allow the deduction of essential information on the morphology of an artefact, both as a whole and for its surface. This provides an invaluable

contribution to the reconnaissance phase to guide the work of the conservator/restorer. Moreover, these capturing techniques represent the bulk of the photographic documentation to which an artifact is subjected and play a fundamental role by depicting an artifact in different moments and different ways, by witnessing and certifying its state of conservation in all intervention phases.
Visible light photography is principally used in 5 ways:

***1. Diffused light*** this is the technique with which photographs are mainly used to document cultural property. It consists in artificially recreating lighting conditions that make the artifact and its chromatic values as legible as possible; trying to eliminate any specular reflection of the surface and trying to respect ordinary conditions of observation as much as possible, with homogeneous illumination on all sides.

Aims of research:
These are photos taken from all sides of an artifact, both before and after restoration to document its general preservation conditions as much as possible.

***2. Raking light*** this consists in illuminating the object of interest with light running parallel to the surface or forming an angle with it of between 5° and a maximum of 15°. Conventionally, the light is placed on the left side or on the upper side for a correct reading of the shadows, but it can also be placed on the right and the lower side, as each side will give different information. This practice represents the first step to examine the surface of an artifact to obtain new information about the technique of execution and investigate its preservation conditions.

Aims of this research technique:
This type of illumination is used to highlight the surface texture of artifacts, making all their surface irregularities visible. It is possible to perceive even the smallest variation in surface depth through the shadows of protruding areas. In the case of painted surfaces, grazing light will make even the smallest elevations of pigment and preparation appear, thus guiding the restorer in the execution of localized interventions and in checking the obtained result.
This technique can also help to reveal the presence of a layer of paint underneath the visible surface, showing variations in planarity not attributable to pigment brushstrokes. It can also provide information about the painting technique, particularly when the paint is applied in a thick mixture, highlighting brushstroke characteristics such as their relief, direction, width, and curvature. Raking light examination is also essential to document the planarity of a medium; canvas, for example, can come loose under the influence of climatic variations or due to its frame's instability. On wooden media, the raking light shows the curvature, distortions, and joints between panels, which are typical deformation phenomena of wooden panels.



***3. Trans-illumination*** this technique consists in illuminating an object from the back and observing the interaction of the radiation passing through its layers. It is mostly used for paintings on canvas, parchments, and paper artifacts. The limits posed by particularly dense supports are insurmountable as light cannot pass through their layers.

Aims of this research technique:
In the case of paintings on canvas, a partial transmission of light may indicate the presence of a dense and colored preparation, or for example, a patch attached to the back due to a tear in the medium. In these cases, the transmitted light can be helpful in evaluating the extent and form of any damage. A pictorial retouching may clearly appear as a darker area when its density, or that of the materials of which it is composed appear more opaque or transparent than the original pigment. Additionally, localized greater opacity may indicate that a retouching or remaking overlaps the original painting.

***4. Macrophotography.*** This consists of photographic magnification on a scale of around 10:1. "Magnification ratio" indicates the ratio between the real physical dimensions of the subject and that of its generated image. Macro lenses, or ones with additional lenses with the application of extension tubes or bellows, are used to obtain these images. Macrophotography allows to isolate small areas of an artifact and focus on details which are not visible to the human eye. Strong magnification allows to visualize the medium's characteristic elements and layers of pigment.

Aims of this research technique:

On mural paintings, this technique allows the detection of degradation phenomena, microscopic pigment losses, repainting and retouching. With sculptures, macro-photography allows the ascertainment of execution techniques, identifying the instruments used. For painted surfaces in general, macro-photography allows to investigate the characteristics of pigments and mixtures, making it possible to image individual grains of pigment and recognize their composition, morphology and color. The field in which the contribution of macro photography is most widely used is the study of cracking (or *craquelure*). This is a phenomenon caused by the different contraction rates between the painting's constituent layers, i.e., the support, preparatory layer and pictorial layer. A detailed examination of the different types of craquelure can clarify their cause. Two main categories can be distinguished: desiccation craquelure and aging craquelure. The identification of an intentional craquelure may allow the recognition of an unintended one.

***5. HD Photography:*** HD or High Definition photography is a technique that assembles several frames captured from different portions of a single object and allows the generation of high definition photographs with an exact reproduction of details. Acquisitions take place with the multiple shot technique and are mainly divided into two categories:

a. Mosaic reliefs: this category includes panoramic images, i.e., images of a vast subject composed by the combination of many individual and partially overlapping captures. The single frames are subjected to *Alignment, Stitching, Merging, and Blending* operations. However, mosaicing is not to be considered as geometrically valid data.

Aims of this research technique:

Mosaicing can enhance the results of all visible light images by extending the field of view and increasing resolution, improving the readability of details. It can also be performed in the non-visible spectrum, although this results in greater complexity when shooting. However, these are advanced shooting techniques only used when a conventional single shot cannot be taken.



b. Multiple framing shots of the same subject: this category includes Focus Stacking techniques to improve depth of field and making double exposures to balance out lighting and reflections. This type of shot is also aimed at RTI post-production.

Aims of this research technique

*Focus Stacking* is useful in artifacts with different levels of depth. This technique allows one to focus on the subject at all its levels of depth. Concerning double exposures, they are best avoided in the diagnostic field but they can be used (in case of necessity) when it is not possible to illuminate the whole surface of a subject correctly. [83].

### 1.3.2.2 Ultraviolet-induced luminescence (UVL) - Emitted radiation or photo-induced luminescence images

Ultraviolet induced fluorescence photography aims to detect the visible response generated by UV irradiation in the 300-400 nm UV band and is the only type of multispectral survey that can provide real-time indications, i.e. by illuminating a subject with Wood light alone[10]. The lamps used for this purpose are made with tubes emitting wavelengths centered at around 365 nm but with a parasite component at about 400 nm due to the tube's inner mercury coating and a small emission in the near-infrared range.

This technique is useful for observing the response of an artifact's surface layers, from the most external ones to the recognition of some pigments and binding products for pictorial and conservation use. Moreover, since the fluorescence of many materials increases in intensity with aging, it allows a preliminary examination of the phases of an artifact's conservation history and to thus recognize chronologically inconsistent interventions.

The phenomenon of fluorescence, or more generally that of luminescence, consists in the emission of a response perceivable by the human eye due to radiation occurring in a more intense portion of the electromagnetic spectrum.

The optical phenomenon can be described in two phases:

***Irradiance:*** higher frequency, lower wavelength

10 Physicist Robert Williams Wood (Concord, May 2, 1868- Anityville, August 11, 1955) studied spectroscopy, phosphorescence, diffraction and ultraviolet light. He is the inventor of the type of glass with which chemist and physicist William H. Byler created the first black light in 1935, called Wood's Lamp.

***Produced fluorescence:*** lower frequency, longer wavelength.

This phenomenon means that only a limited quantity of the irradiated light produces a response in the visible field, and this is why it is necessary to use sources that produce very powerful and concentrated radiation (UV-A 300-400 nm with a peak at 365 nm). Shooting needs to be done in the dark, and with extended shooting times, it does not require dedicated cameras because the acquisition takes place in the visible light field.

Aims of this research technique:

Observation of fluorescence makes it possible to identify the characteristics of an artifact's surface layers, starting from the most external stratigraphic sections such as paints and protective film-forming layers. It allows the recognition of certain pigments and binders and to distinguish adhesives and pictorial conservation products. For the correct interpretation of ultraviolet fluorescence, it is necessary to consider both the intensity of responses and their chromatic qualities. Therefore the post-processing of the acquired data requires particular care in order to obtain consistent results [82], [83].

### 1.3.2.3 Ultraviolet-reflected (UVR) - Reflected radiation images

This technique consists in detecting the UV spectral band invisible to the naked eye. The acquisition requires a modified camera for IR-UV vision and dedicated optical filters. Even if the irradiation is performed with the same instrumentation used in ultraviolet fluorescence (UVL), UV Reflectography does not allow real-time observation. The acquired data needs to be displayed and digitally processed. An artifact's colors are not detected, as the information acquired corresponds to a portion of the spectrum not perceived by the human eye and is therefore displayed as grayscale tones.

Aims of this research technique:

information derived from this technique concerns:

film-forming layers of paint, their distribution and qualities.

the identification of certain pigments independently from ageing;

Preservation and conversation interventions above and below varnish

Densification of material.



### 1.3.2.4 nfrared-reflected (IRR) - Reflected radiation images

Infrared radiation extends from the limit of the visible region, on wavelengths longer than red. It occupies a large part of the electromagnetic spectrum, from about 750 nm to about 400,000 nm. In particular, it allows the distinction of Near Infrared (NIR), in the circa 780 to 2500 nm range, from Medium Infrared (MIR) in the 3000 to 30000 nm range and far-infrared (FIR) which goes from 30,000 nm to microwaves. The infrared band in diagnostic applications for cultural heritage presents different types of acquisition and processing depending on the selected portion of spectrum under examination. Standard CCD and CMOS sensors of digital reflex cameras modified for IR-UV can record NIR emissions of wavelengths up to about 980 nm. Specific, recently available, and costly instrumentation allows the digital recording of wavelengths images up to 2400 nm[11].

The possibilities and limitations of this technique are related to the reactions of materials to different wavelength radiation. The opacity or transparency of a layer of paint is directly related to the physical characteristics of its constituent materials, in particular to the diffusion and refraction characteristics of the incident radiation. On these aspects, researchers studying infrared reflectography based on Kubelka-Munch's theory that describes the optical characteristics of paint layers have clarified how materials respond to near-infrared NIR light. It was thus demonstrated that the ability of a layer of paint to cover a background depends primarily on its scattering power and that as the wavelength of incident light increases, the scattering phenomenon decreases and, with it, the materials' covering power. In painted surfaces, pigments have a more significant covering power depending on the average size of the particles and their color shade. A finely ground pigment increases its diffusion capacity and, therefore, its covering power. Dark colors are more opaque than light colors. [84].

To allow its IRR investigation, an artifact is illuminated by common incandescent lamps or sunlight. Its chromatic component is not expressible because the information belongs to a portion of the spectrum not perceived by the human eye. For this reason, the acquired images are translated into grayscale. The acquired data

11 Among them we can mention*: Artist camera by Art Innovation* with two IR filters 780 up to 980 and 980 up to 1150nm (plus UVR and visible light); *Ingaas Camera* (e.g. Osiris) with IR filter from 980 nm to 1700nm; *Jade camera by Cedip Cooled* ingaas sensor with ir filter from 980 to 2200nm; *Hamamatsu Vidicon tube Analog* with IR filter from 980 to 2400nm.

can thus be digitally processed to obtain false-color images. [82].

Aims of this research technique:

this technique allows to capture images from layers below the films of paint, as infrared radiation is extremely penetrating. In addition, many materials, such as organic binders and colorants, are generally transparent at infrared wavelengths. This technique offers good results in analyzing preparatory drawings, the artist's *pentimenti*[12], and allows to identify the painting's stratigraphic veiling films.

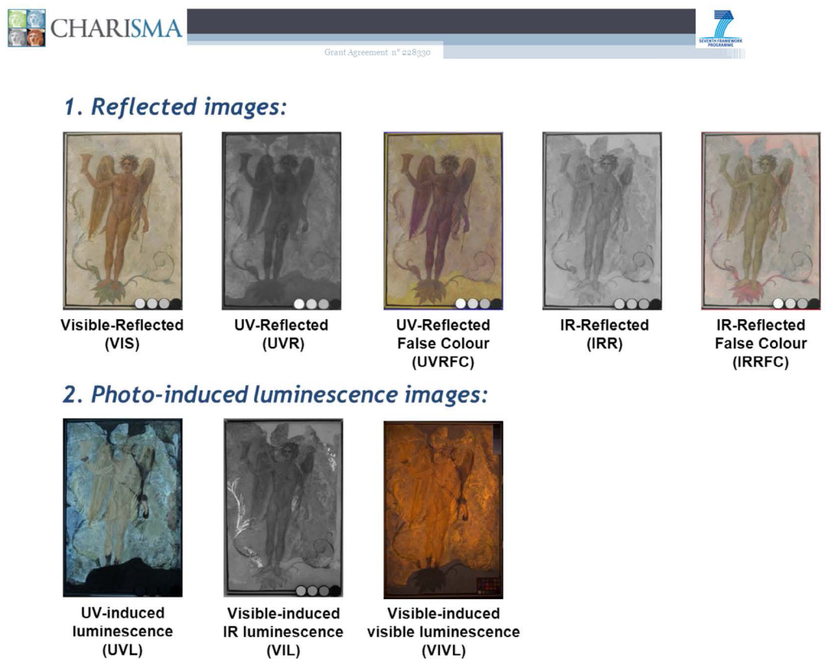



Figure 1.13
An example of the full suite of images that can be acquired using all the multi-spectral imaging techniques described above- Wall painting fragment from the British Museum (Winged youth from the Tomb of the Nasonii, 1883,0505.5).ù
Source:
Dyer, Joanne, Giovanni Verri, and John Cupitt. 2013. Multispectral Imaging in Reflectance and Photo-Induced Luminescence Modes: A User Manual. 1st ed. eds. Joanne Dyer, Giovanni Verri, and John Cupitt. Web publication/site: Online: European CHARISMA Project.

12 Painting modifications performed by the same author during the creation of a painting.

# Section 1.4 Thematic Maps

Graphic documentation in the conservation process is very elaborate since the criteria of data evaluation and the criteria of practical execution need to be coherent over time to create an effective and efficient simplification and standardization of procedures. In this section, we refer to the process of logical and graphic structuring of thematic maps started by Francesco Sacco in the 90s [85], within the Istituto Centrale del Restauro di Roma ISCR. The structural approach started in those years is the same used today, with some computer applications described in paragraphs 1.5 and 1.6. As enunciated, the thematic maps result from an accurate, critical analysis of the artifact carried out by the conservator who uses his personal experience and various diagnostic investigations to transcribe the technical information necessary to plan the conservation and preservation activities. If well-executed and based on scientifically valid data, they represent the best support tool for planning interventions and evaluating the types, the severity of the damage, and their percentage of incidence on the overall surfaces of the work.

## 1.4.1 Subdivision of data into Categories and Classes

The process of graphic documentation follows temporal criteria: it starts with the morphological representation of the artifact and the list of its constituent materials, followed by the representation of the changes over time. It ends with the description of implemented conservative interventions. All the collected information forms a complex set of non-homogeneous data, which can be structured according to what we may call categories and which, in turn, can be formed by other sub-sets called classes ordered hierarchically among themselves and within the categories. Below is a descriptive list of the principal and indispensable categories and classes for restoration works (shown in figure 1.14.):

***a. Category – Artifact's Constitutive procedures:*** every artifact of historical and artistic interest is produced with techniques that transform raw materials into multiform and intricate structures. This category describes the raw materials that constitute the original artifact and the procedures that have allowed its formation as an artifact. This category consists of two subsets of data:

> ***Class - execution techniques:*** This class represents the physical traces present on the manufactured product from the preparation and processing procedures carried out in the execution phase. If recognized, the instruments used must also be indicated.
>
> ***Class - constituent materials:*** this class represents materials present in the work, recognized by visual inspection or by specific chemical-physical investigations carried out on samples.

***b. Category - State of fact:*** this category describes the artifact's condition at the time of document compilation. It includes the changes that occurred on the artifact until that moment, produced by natural or-and anthropic factors. This category consists of two subsets of data:

> ***Class - State of preservation:*** describes the effects caused on the artifact by natural or anthropic factors and specifies the characteristics of these causes-voluntary, involuntary, accidental, etc.
>
> ***Class - Historical Interventions:*** this class groups the effects of voluntary anthropogenic causes, i.e., related to previous conservation and restoration interventions.

***c. Category - Conservation Interventions:*** this category describes which interventions have been performed on the artifact, identifying also the area of intervention. This data has a huge documentary value and provides the basis for the artifact's conservation over time and for future conservation and preservation interventions. The thematic maps related to this category, if well performed, fa-

cilitate the identification of the problems present on the artifact, allowing them to carry out predictive analysis and spot-on conservation interventions.

***d.Class - Diagnostics:*** This group of data is common to each category and represents the different diagnostic techniques that have contributed to clarifying the nature and origin of all the information present on the artifact.
This class has two subclasses:
***Analytical investigations:*** researches carried out on the entire artifact or test samples
***Technical Testing:*** preliminary tests of cleaning, consolidation, integration, etc. carried out by the conservators before proceeding with the executive project- i.e., with the final restoration-.

## 1.4.2 Distinction between data models, correct graphic and topographical indications

Below is a list of the essential features of correct graphic documentation.

***1.Specific topographical indications:***

The main problem found in the creation of thematic mapping is to reconcile, in the same graphics elaboration, representation of the geometric-dimensional and iconographic characteristics of an artifact and its historical-conservative characteristics. The graphic representation of the artifact cannot be approximate but must respect the correspondences that, in reality, exist between the areas of the artifact and those of its historical-conservative features. Therefore, correct graphic documentation must always define the reference system and the individual points' objective identification.

***2. Distinction between Models***

As just stated, the documentation consists of two different types of superimposable representations called Models: a topographical morphological one, and the other referring to historical-conservative features.

***a. Object Model / Artifact Model:*** this is the graphic/morphological representation of the object. Concerning this model, different problems may occur,



depending on the different types of works to be represented:
***Technical/geometric problems:*** since the representation of the object must necessarily be performed on a two-dimensional plane, in some cases, the artifact itself defines its spatial conformation (e.g., sculpture or architecture), but in other cases, the artifact can be located on a support (e.g., mosaics, frescoes) or has an irregular or figurative confirmation, so it is essential to choose the reference system and the most appropriate type of projection to represent each artifact.
***Illustrative problems:*** the representation of the iconography and figuration must be synthetic and easily readable. Therefore, the necessary and sufficient signs should be mapped to make their essential aspects recognizable; that is, those essential to localization of the historical-conservative characteristics.
***Graphic problems:*** the iconographic and figurative representation signs must appear unequivocal and be distinguished from the conservative historical data signs.

***b.Model of information:*** it is the graphic representation of the historical-conservative data, that is, all those facts and phenomena concerning the artifact's constitutive procedures and its preservation conditions. Data relative to this model will have to be represented following the categories system's structure, therefore on different graphic tables numbered for a chronology of execution, each containing only those items grouped in the different classes.
The information model is realized using graphic symbols (pattern, symbols, alphanumeric annotations) overlapped to the first model.
This model is most affected by problems of normalization for both textual and graphic documentation language. As stated in section 1.1.2, there is a specific glossary and precise graphic indications only for stone and ceramic artifacts.
The conserver/restorer must follow as much as possible the NORMAL recommendations and the glossary produced by the ICOMOS-ISC association and use graphic choices of data representation based on the recommendations for the correct use of graphic symbology, detailed in the following point.

*c. Correct use of graphic symbology*

Below is a list of the main recommendations to follow for correct and easy-to-read graphic documentation:

- Keeping the distinction between main figure and background, i.e., preserving the full readability of the information model and the object model that overlapped form defined graphic documentation.
- Localization of data concerning the nature and the conservative state of the object using appropriate patterns to define not only the exact topographic extension but also their quantitative consistency.
- In case of several data overlapping, it is necessary to maintain full readability for the individual overlapping *partners*.
- Use of color in the creation of symbology can help readability of the documentation. In this case, printing proofs must be made to ensure the correct color result.
- The symbology scale must be related to that of the artifact's representation.
- Selection of the most appropriate and innovative graphic techniques to carry out graphic documentation, favoring digital techniques and avoiding hand-made.
- Adopting the same scales for thematic maps of the same category.
- Avoiding all drawings and signs of parts which could more easily be represented by a photograph, and also purely decorative signs with no informative content.

Regarding this last point, it is important to specify that the object's model can be represented either with a drawing or with a digital photographic image replacing the graphic model (Fig.5.6). In on-site practice, photographic based documentation is the most used by restorers for their information collection [86]. In this case, photographs must be free of objects extraneous to the artifact and reflect its formal geometric criteria. (The concepts related to photographic acquisitions for documentation are expressed in section 4.1.1.).



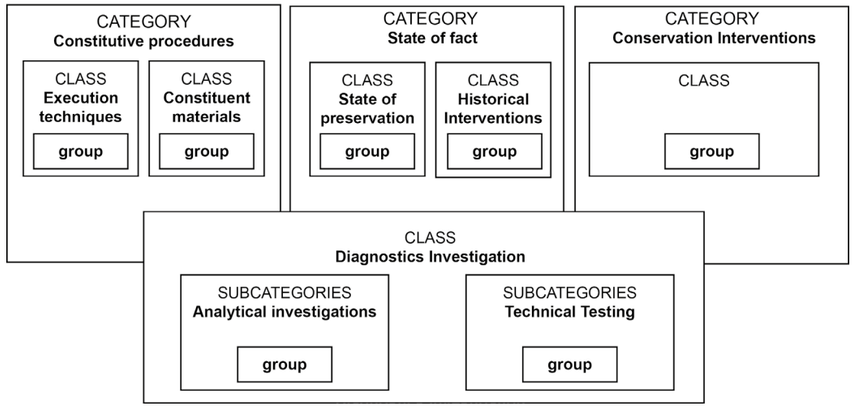
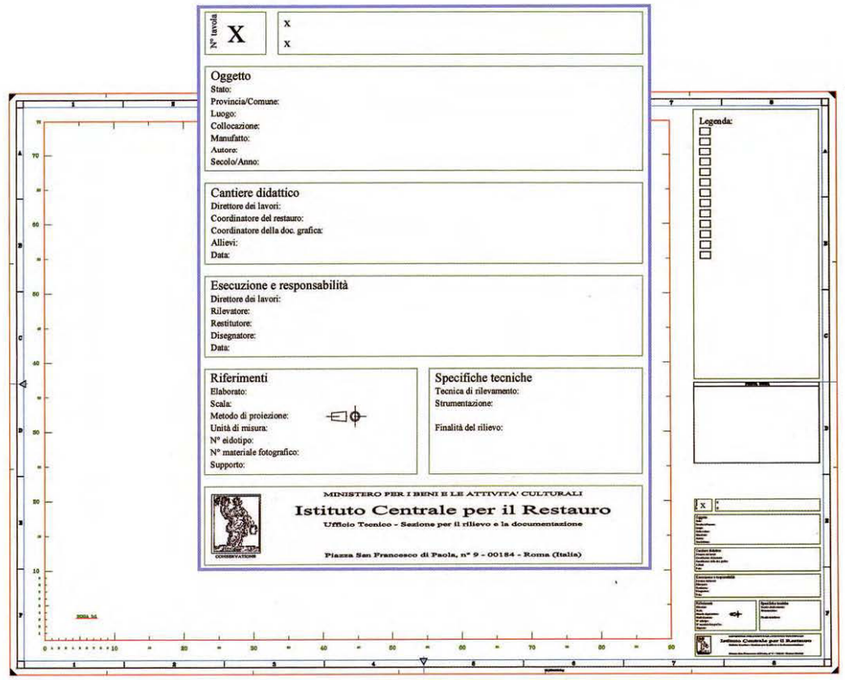



Figure 1.14
General scheme of the relationships between the sets that contribute to the creation of a graphic documentation.

Source: Sacco, F. 2002. Sistematica della documentazione e progetto di restauro. Bollettino ICR, (N.S.)4(1); 28-54, pp35




[1]Figure 1.15
Example of template for thematic maps- ISCR ROMA.

Source:
Sacco, F. 2002. Sistematica della documentazione e progetto di restauro. Bollettino ICR, (N.S.)4(1); 28-54, pp35

# CHAPTER II

# State of the Art

Even though the importance of documentation has been universally recognized, and significant steps have been made in recent years in the application of innovative documentation systems, many problems still remain unresolved.

The number of problems connected to artifacts' analysis and digitalization has led many institutes and individual researchers towards the scientific approach of optimizing diagnostic investigation  and automatism of graphic surveys.
This section analyzes the main problems present to date in the documentation process and mentions the research projects focusing on their solution.
Also mentioned are the projects which have allowed us to reflect on the development of the proposed methodology and which we believe can be implemented to strengthen it.

Section 2.1

# Issue related to the creation of thematic maps

As we have seen, standardized techniques of architectural and archaeological survey (especially those related to the survey of constituent materials in buildings external surfaces') have guided the development of current thematic maps for conservation planning, not only of buildings and monuments, but of all other cultural heritage categories.

For this reason, only in the context of historical architectural monuments and archaeological sites can restorers rely on professionals, e.g., architects, and ad hoc standards for the generation of thematic maps.

For buildings' interior decorations and small movable objects such as painted canvases and wood panels, sculptures, and utensils, conservators-restorers often try to apply the same criteria as architectural surveys, but without a standard methodology. The lack of standardization concerns data collection and acquisition methods, the textual/graphic language, and the software use.

## 2.1.1 Textual and graphic vocabulary

It can be observed that cards' compilation is generally based on the repetition of terms belonging to a vocabulary created or accepted by a group of people who recognize and use it. The absence of specific vocabulary or the conceptual uncertainty of single entries makes the card an ineffective tool in terms of objective study method [86]. Today, language and graphic ambiguity is still such that the contents of thematic maps can be subject to different interpretations. In fact, in certain areas, there is no standardized documentation methodology that adopts univocally recognized criteria.



As described in section 1.2, some standards are currently in use for digital architectural design[1], [16], [17], [18], [19], [20], and the UNI Beni Culturali NorMal (*Norme Materiale Lapideo*)[2] standards [22] referring mainly to undecorated stone material, mortars, and ceramics.

In the absence of normalization, it is often impossible to compare the results acquired by the various research and conservation works since there is no common language to offer an easy and all-embracing divulgation of the proposals and results obtained, especially among operators with different cultural backgrounds.

## 2.1.2 Software in use

The standardization problem also extends to the software applications in use, as there isn't a specific software currently adopted. As described in paragraph 1.2, higher education schools and superintendencies tend to use SICAR to obtain a consistent and easily consultable database. On the other hand, individual professionals tend to adopt CAD tools that differ according to their needs. Especially in the context of canvases, painted panels, ceramics, frescoes and mosaics, archaeological or other findings, restorers often empirically use a commercial vector graphics or image processing software. All the software in use, though, presents significant practical limitations:

as far as CAD is concerned, it's perfect for the mathematical processing of geometric data. However, it is particularly challenging to use when the graphic relief to be produced consists in a mainly figurative and articulated representation, characterized by irregular and non-geometric edges and shapes. Moreover, the difficulty with this software is mainly related to mapping the state of conservation, because the various types of degradation generate on the object's surface areas characterized by irregular shapes and highly jagged edges.

1 Among the standards, there are the Intemational Standard Organizatlon ISO/3567, the technical services of the Fort Worth District of the US Army Corp of Engineers, CADD Council standard (promoted by NIBS) and the national standard in the construction industry NCS.

2 Among the documents produced and published by the commission, directly concerning the topic of graphic drawing are the NorMal 1/80 "macroscopic alterations of the stone materials, lexicon", and the NorMal 17/84 "metrological elements and dimensional characteristics: graphical determination". The UNI 10924:2001, "Cultural Heritage, Mortars for constructive and decorative elements, Classification and technical terminology: definition and description of mortars", and also the UNI 10739:1998, "Cultural Heritage, ceramic technology, terms and definitions", have acquired the value of Norm.

CAD drawing tools tend to geometricize the areas, with the result of making approximate thematic maps. In addition, CAD does not allow you to organize your files in a structured database.

CAD and SICAR software merely allow to insert raster images, without the possibility of interacting with pixel values. It is essential to specify that color data is crucial in characterizing some types of artifacts, particularly those with a decorated or painted surface, and for which, for example, specific color conservation problems need to be analyzed. With this kind of software, there is no interaction between raster and vector graphics, and each graphic survey is drawn by hand by the operator.

This free-hand element has always been recognized as a positive characteristic, as the free drawing allows operators to act according to their experience and knowledge of the artifact, performing a specific circumscription of the identified areas. Actually, this necessary free-hand method causes extreme approximation in operators drawings, especially when the areas to be mapped are substantial (a condition that applies in most cases). This results in a high level of subjective interpretation that makes each thematic mapping different from any other, even if carried out by the same operator on the same photographic base.

Furthermore, the complexity and extended time needed to carry out the entire process leads superintendencies not to require graphic documentation in the restoration project. For the same reasons, often restorers produce graphic documentation after the restoration project has been completed, or represent only the essential information (thus making the documentation incomplete), or even rely on external operators (thus spending money, not included in the restoration project's budget), or do not perform it at all.

In more recent years, the development of low-cost and easy-to-use Geographic Information System software has made it possible to use this technology for even non-geographic projects, yet containing spatial attributes and mapping elements [87],[88],[89]. Starting from relatively large areas, GIS has then been used on mobile artifacts; especially in Italy, Spain, and Portugal, experimentation on the statistical analysis of painted canvas and tables degradation is underway



[90],[91],[92],[93]. Two GIS software products have been used for these experiments: QGIS- free and open-source[3] , and ArcGIS[4], an Esri proprietary software. In particular, QGIS has proven to be widely used for scientific research in territorial, archaeological, and art history fields. For this software, interesting plug-ins have been developed, including the *Semi-automatic Classification Plugin* that combines multispectral images and raster analysis, allowing an operator-controlled semi-automatic classification of environmental remote survey images, and providing a tool for a speedier territory classification process [94]. Another interesting plug-in for raster analysis and classification is the *MagicWand*[5]. This plug-in activates a mapping tool allowing users to extract a polygon from a raster image with a single click, according to pixel colors.

### 2.1.3 Documentation accessibility management

Further fundamental issues are related to documentation accessibility and usability. Thematic maps are generally used by different types of professionals operating at different times and in different ways, thus representing a formal and unequivocal tool for communication, comparison, and guidance for following conservation and preservation operations. Graphic documentation should always be well archived, accessible, and usable; therefore, it should be possible to obtain or find information when and where it is needed.

Unfortunately, to date, superintendencies still require documentation in print and store digital files using obsolete media that tend to become unusable within few years. In the best cases, digital documentation is provided by paid software, making it necessary to purchase the licenses to manage them. Moreover, consultation of many important projects is hindered by the use of specifically designed systems, therefore accessible only to the small group of people who contributed to their realization. This results in uneven media and databases which cannot be digitally consulted.

3 https://qgis.org/it/site/

4 https://www.arcgis.com/index.html

5 https://github.com/GianlucaSilvestri/MagicWand

For the above reasons, for many years now, attention has been turned towards the use of QGIS even in the archaeological field. In Italy, a plugin called pyArchInit[6] has been developed for QGIS, to answer the ever growing need among archaeologists to digitalize excavations' documentation, using software that can manage alphanumeric and multimedia topographic data in a single solution [95],[96]. PyArchInit has been designed to provide stability, development, and easy installation and updating over time. The ultimate goal is to provide a GIS platform with high scalability between different operating systems, in which alphanumeric filing, GIS geometries, and multimedia data can fit within a single system to keep data integrity as strong as possible. The first part of the project was planned and carried out to allow in situ documentation management for ongoing excavation sites. The system has also been designed to manage web data in the future, both for the data-entry phase and further consultation via Web-GIS. At the moment, it can be used both as a stand-alone application for excavations' Stratigraphic Unit cards input and as a plugin for QGIS. Moreover, in the last year, card models have been aligned with the ICCD models, internal search engines have been built, plus specific queries allowing to work remotely.

## 2.2 Diagnostic investigations Study

The main issues concerning diagnostic investigations, are related to white balance, post-production, and interpretation modes.

### 2.2.1 White balance and post-production

Digital diagnostic images require a colorimetric correction process, both during acquisition and in post-production.

Generally speaking, all adjustment and balancing operations greatly influence the interpretation of multispectral images, as they modify the visibly expressed color tones, which correspond to the wavelengths reflected by surface materials. In the case of Induced Luminescence Images which have a response in the field of visible, such as Ultraviolet-induced luminescence (UVL), Visible-induced infrared luminescence (VIL) images, Visible-induced visible luminescence (VIVL) images,

6 http://pyarchinit.blogspot.com/
https://sites.google.com/site/pyarchinit/



artistic materials show different grades and tones of fluorescence according to their composition and aging. Therefore, white balancing during shooting can substantially impact the fidelity and reproducibility of images, making interpretation inaccurate and comparisons between images taken at different times and with different settings inconsistent. Regarding reflected images, instead, white balancing is an issue mostly related to post-production, with cases of false-color reflected images, such as Ultraviolet-reflected false-color (UVRFC), Infrared-reflected false-color (IRRFC).

To obtain consistent and comparable data, standards should be followed, currently represented by the results of the British Museum's Charisma Project [82].

However, these standards are not easy to implement, and in practice, more readily available commercial colorimetric references are used, which do not offer optimal results.

In addition, cameras available on the market are designed to provide aesthetically pleasing images and not scientific analysis of artifacts and, as a result, they may make undesired changes to the captured multispectral images. Camera incorporated adjustments include contrast, brightness, sharpness, Automatic Gain Control (AGC), which controls the "dynamic range" in low light situations, white balancing. To avoid such problems, in addition to the Charisma Project, several handbooks and scientific articles have been published to illustrate the correct use of colorimetric references for multispectral imaging [83],[97].

### 2.2.2 interpretation of diagnostic images

Interpretation of multispectral images varies depending on the type of technique in use, investigated artifact, and its age. Concerning grayscale monochromatic images such as Infrared-reflected (IRR) and Ultraviolet-reflected (UVR), reading and interpretation difficulties depend exclusively on the artifact's state of preservation and the information researched, as characteristics are distinguishable only through variable transparencies and contrasts. Referring to color diagnostic images, such as induced luminescence images and false-color reflected images, in which we can find material reflectance effects, identifying the researched characteristics is more complicated. These in fact appear on the artwork surface in more or less homogeneous areas of color and in ever varying chromatic shades. These

chromatic variations depend on the techniques with which the artifact was made, its surface materials, and their aging.

In addition, materials, such as pigments and binders, are layered and blended together, and application techniques vary greatly depending on the historical period. As a result, materials are reacting in multiple spectrum bands simultaneously with different levels of intensity. Therefore, recognition of characteristics through the fluorescence phenomenon falls under an interpretative process which depends on examiners' experience and available reference literature for that specific case. Over the years, many scientific researches have been conducted in support of fluorescence materials recognition, the main ones including:

- application of a mathematical model based on Kubelka-Munk's theory, studying the pigment-binder interaction [98],[99];
- a particular false color imaging technique called ChromaDI which enhances the differences between the optical behavior of the various pigments in the visible image, taking into account the changes that occur during the transition from short to longer wavelengths [100];
- development of a methodology to classify different pigments through Hyper Spectral Imaging (HSI), which acts in the Short Wavelength Infrared (SWIR) region [101].

Finally, it is crucial to specify that, regardless of the type of technique and artifact investigated, archaeologists and conservators/restorers must always be involved in diagnostic investigation interpretation and understanding, being the only ones who have knowledge of artifacts' material characteristics.

CHAPTER III

# Theoretical and technological bases for a new methodology

Summarizing the themes related up till now, we can capture three fundamental elements:

i. raster digital images appear as the main tool for diagnostic investigation and to document artifacts' *existing conditions* and this is why they have a central role among the problems faced within our research;

ii. *"Graphic documentation in restoration of any artefact requires the design of a non-illustrative, non-raster vector drawing, i.e., without shading and with topographically consistent closed polygons".* Graphicization carried out through vectorial drawing allows to activate a data synthesis, discrepancy and characterization process providing immediately readable and analyzable results;

iii. Problems concerning the creation of thematic maps based on image interpretation (diagnostic or not) depend on the lack of a software application allowing to carry out a statistic analysis process on raster images, and consequent extraction of features through raster to vector conversion.

Having identified the main themes and problems to be solved, research was addressed towards definition of a semi-automatic methodology, allowing to combine procedures relating to image analysis with those for specific conservation documentation, considering a few fundamental requisites:

***semi-automatism:*** automatism cannot be considered a requisite within the methodology, as each artifact of historical-artistic interest presents its own conservation history which, in addition to peculiarities relating to executive techniques, constituent materials and to the kind of degrade, make it one of a kind. Furthermore, the appearance of features describing such peculiarities changes in each phase of the conservation intervention. For all these reasons, it is necessary that all methodology processes may be guided by a conservator/restorer, whose inspecting and guiding role can in no way be omitted. The methodology's aim is not to substitute operators within the documentation process, but to facilitate their work in recognizing and extracting features.

***Requisites for the appropriate Software:*** for efficiency reasons, it must be possible to apply methodologic process in one software, guaranteeing data consistency, reproducibility of results and documentation accessibility. Considering the research project's aim and the operators' target reference, software must be easy to use and must allow conservators/restorers to carry out all operations through a user-friendly Graphical User Interface. Also, the chosen application must communicate with currently used documentation software.

Based on such requisites, the following paragraphs describe all assessment and deep analysis carried out on three main topics which allowed to consolidate the methodology:

- Raster image elements useful to define qualitative parameters to be followed for methodology purposes;
- Algorithms to facilitate features' recognition and extraction, morphological operations for shape cleansing, raster to vector conversion algorithms;
- Research for software applications useful to the methodology, paying particular attention to the possibility of raster analysis.

These topics have been treated in detail and associated to the problems related to cultural heritage documentation, as the methodology's goal is to offer conservators/ restorers a model to obtain an effective graphic documentation, in a shorter time and appliable to projects and statistic purposes.

Section 3.1

# Background on Raster Images: basic terms and considerations

To develop a description of the methodologic process, it's essential to define what a digital image is, which are its components, visualization typologies and ways of analysis.

## 3.1.1.Digital image creation process

A digital image is the conversion of continuous data- electromagnetic waves- into discrete data - electrical impulses. Mathematically it has been defined as a 2D light intensity function $f(x,y)$, where $x$ e $y$ are spatial coordinates and the amplitude of $f$ of $(x,y)$ corresponds to the light intensity (or gray level) of the image at that point. The value or amplitude of $f$ is a positive scalar quantity, whose physical meaning is determined by the source that generated the image [102]. When the image is generated by physical processing, its intensity values are proportional to the energy radiated by the physical source; in our case, the electromagnetic waves.

In this case the function $f(x,y)$ can be characterized by two components:

illumination component $i(x,y)$, which represent the quantity of direct incident light on the scene;

reflectance component $r(x,y)$ which represent the quantity of light reflected by objects in the scene.

Therefore, an image can be defined as follows

$$f(x,y)=i(x,y)r(x,y) \tag{1}$$

Where the nature of $i(x,y)$ is determined by the source of illumination



$$0<i(x,y)<\infty \tag{2}$$

And the reflectance $r(x,y)$ is between 0 (total absorption) and 1 (total reflection) and is determined by the characteristics of the object

$$0<r(x,y)<1 \tag{3}$$

Specifically, in digital raster images the physical phenomenon is converted through a sensor into a continuous sinusoidal electric voltage. In the case of photographic images, acquisition occurs through CCD (Charge Coupled Device) sensors assembled as a two-dimensional matrix of $M$ ows and $N$ olumns, called array, which can measure more than 4000 x 4000 elements (Fig.3.1). The array of sensors coincides with the machine's focal plane and produces output data proportional to the total light energy received.

The continuous data from the light intensity function $f(x,y)$s confined in a discrete range of values through two processes called sampling and quantization.

***The sampling process*** divides the continuous input signal into discrete points by assigning spatial coordinates $(x,y)$ within the array. The discrete points can be defined as samples and are represented by integers. Each sample is called a pixel or pel, short for Picture element.

The three parameters typically used to sample signals are:

*i.**Sampling interval:*** the interval between samples determines the *spatial resolution* of the sampled signal, which can be defined as the number of acquired samples per time unit. With an increase in resolution, representation of the other frequencies becomes more accurate, i.e. of the smallest chromatic variations and details.

*ii.* ***Sample accuracy:*** the representation of the signal through a fixed number of bits per sample.

*iii.* ***Sampling extent*** is calculated based on frequency with Fourier's transform and defines the amplitude of each sinusoidal wave which contributes to breakdown the signal.

***Quantization process*** is the subdivision into discrete points of the luminous intensity values of $f$. In this phase, a range of input luminosity values are "mapped" in just one output value. This happens because in analogic signals (electromagnetic waves) the range of values between two extremes is infinite, whereas in the digital world only a certain number of values can be represented. Quantization can be either scalar (SQ) or vectorial (VQ). In SQ, each sample is quantized individually, while in VQ blocks of samples are quantized together.

Luminous intensity value is quantized in a number $Ng$ of $L$ levels of gray, generally consisting of an exponent of 2, defining the "depth" of the information

$$L = 2^K \tag{4}$$

Data can be quantified in different levels of precision depending on the bits used. The number of bit $b$ needed to store an image of $N \times N$ size, with $2^m$ levels of gray is:

$$b = N \times N \times m \tag{5}$$

Keeping a maximum precision of 64 bit, it's possible to carry out any kind of analysis of the surface features, without loss of information.

The collective set of measured values is defined as the *dynamic range* [1] of an image and corresponds to the luminous intensity diffusion from the darkest to the lightest point present on the scene. Images with an elevated dynamic range offer richer information about constitutive visual and material aspects of the reproduced subjects.

Once acquired, a raster image can be requalified and resampled, but it won't be possible to obtain new information if not already present in the image itself.

Thus, it is crucial to use acquisition devices which allow to obtain images with high spatial resolution; particularly in the field of artistic diagnostics and of documentation photography, working on insufficient data would affect methodology goals.

1 The term "dynamic range" comes from music, where it refers to the spread between the softest and highest volume levels in a song, performance, instrument or recording.



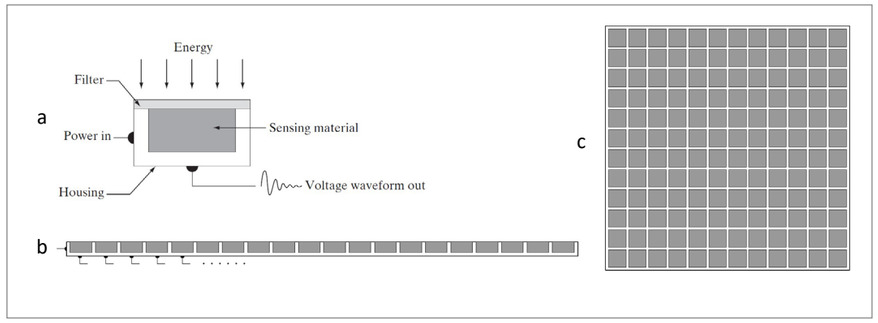



Figure 3.1
a) Single sensor
b) Inline sensors
c) Matrix/array of sensors
Source:
Gonzalez, Rafael C., and Richard E. Woods. 2012. Digital Image Processing (2nd Edition). 2nd ed. ed. Marcia J. Horton. New Jersey: Prentice Hall.

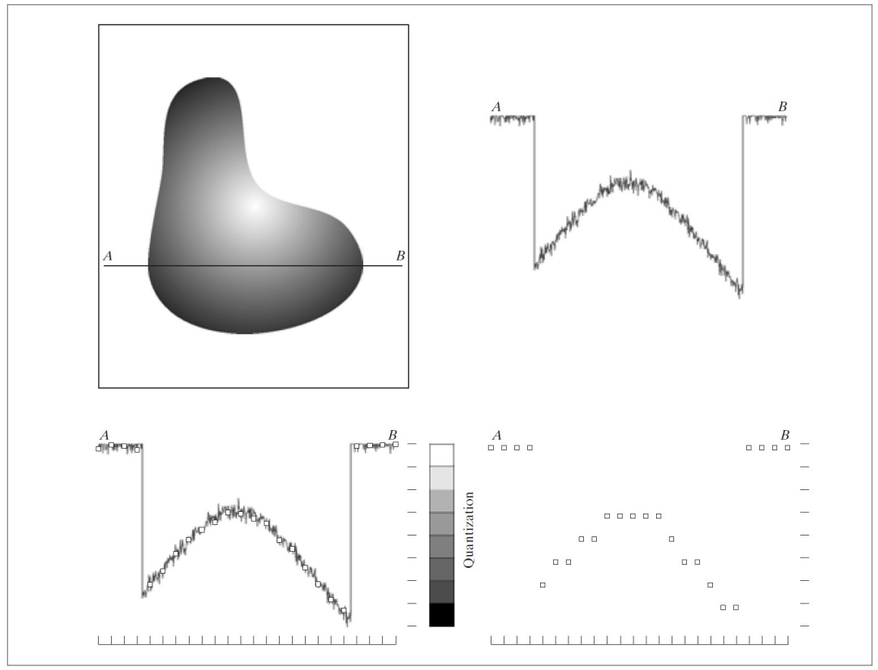



Figure 3.2
Generation of a digital image.
a) Continuous image
b) Analogic scan line
c) Sampling and Quantization
d) Digital scan line
Source:
Gonzalez, Rafael C., and Richard E. Woods. 2012. Digital Image Processing (2nd Edition). 2nd ed. ed. Marcia J. Horton. New Jersey: Prentice Hall.

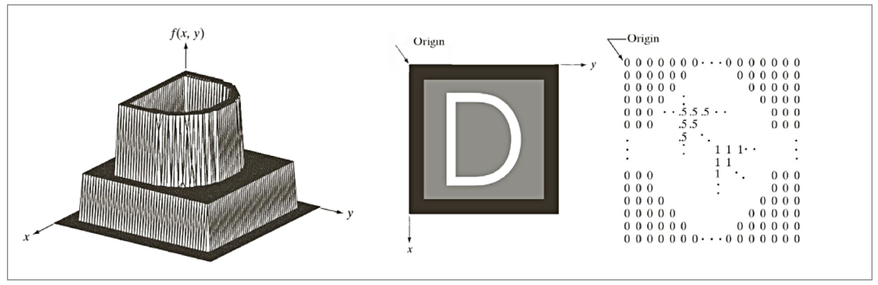



Figure 3.3
Different representations of the same digital image.
a) Grayscale image described in relief
b) Image displayed on a video device as a set of grayscale values.
c) Image displayed as a two-dimensional matrix (0, 0.5, and 1 represent black, gray, and white, respectively).
Source:
Gonzalez, Rafael C., and Richard E. Woods. 2012. Digital Image Processing (2nd Edition). 2nd ed. ed. Marcia J. Horton. New Jersey: Prentice Hall.

## 3.1.2 Types of raster images

Depending on acquisition and optimization modes, we have different types of raster images. The types used in the researched methodology process belong to the four listed categories.

### 3.1.2.1 Binary Images

In a binary image, each sample (pixel) within the array has a discrete value corresponding to 1 or 0. To produce a binary image, it's necessary to use just one bit per pixel. Most of the functions used in image elaboration software interpret pixels with value 1 as belonging to a *region of interest* ROI, i.e. to the researched object or feature, and pixels with value 0 as background. Binary images are used to indicate which parts of the image must be elaborated or extracted, and in this case are called *Binary Masks.* A process collecting different discrete values (i.e. values from 0 to 255) into 0-1 values is called *binarization process.*

### 3.1.2.2 Grayscale Images

In a grayscale image, each pixel takes a discrete value in an interval defined as based on the number of bit per used pixels. Using 6 bits, we have a value interval of 0-63, per 8 bits we have 0-255, per 10 bits 0-1023, in which 0 corresponds to the minimum luminous intensity value (black) and 63-255-1023 correspond to the maximum luminous intensity value (white). High interval values correspond to high *dynamic ranges*.

### 3.1.2.3 TrueColor Images

Color images are formed by a combination of three grayscale images, called *Channels.* In each channel are held the discrete values (samples or pixels) corresponding to a specific electromagnetic wavelength relating to visible light, which we can call bands. The pixels present within the color images array are identified not by a single value but by a triple value for each pixel, corresponding respectively to each band. By convention, color images are formed by three *Channels,* corresponding to the Red, Green and Blue bands. From which originates the RGB acronym. The number of bits used to represent each pixel in RGB space is called pixel depth. Color models and representations will be treated in section 3.1.4.



### 3.1.2.4 Multispectral and Hyperspectral images

A multispectral or hyperspectral image is a kind of color image which includes three or more grayscale channels, belonging to the whole electromagnetic specter extension, beyond the visible. Belonging to this category are also the diagnostic images treated in chapter 2 such as the Infrared-reflected (IRR) images, Ultraviolet-reflected (UVR) images, False-color reflected images, Ultraviolet-reflected false-color (UVRFC) images, Infrared-reflected false-color (IRRFC).

### 3.1.2.5 False Color or hybrid color

By false color we refer to images made for diagnostic purposes, combining information coming from acquisitions in different spectral bands or from portions of bands. They are the result of the combination of three or more grayscale channels of the same subject. Usually the individual channels come from different light diffusion and acquisition modes, for example channels can come both from multispectral images and from visible light. False color images can also be created assigning a specific color to a group of monochromatic intensity values in grayscale. The result is a depiction in artificial colors, thus false, as in not corresponding to the original color.

TrueColor, multispectral and False color images can be visualized in two ways, in fact channels can be examined as combined, to form the color, or separately in grayscale.

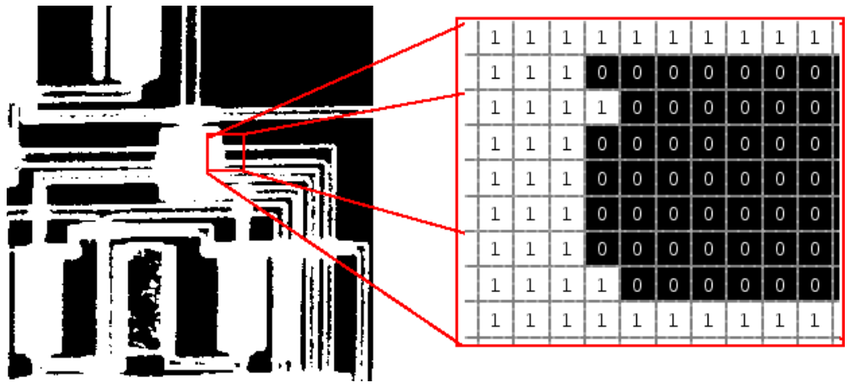
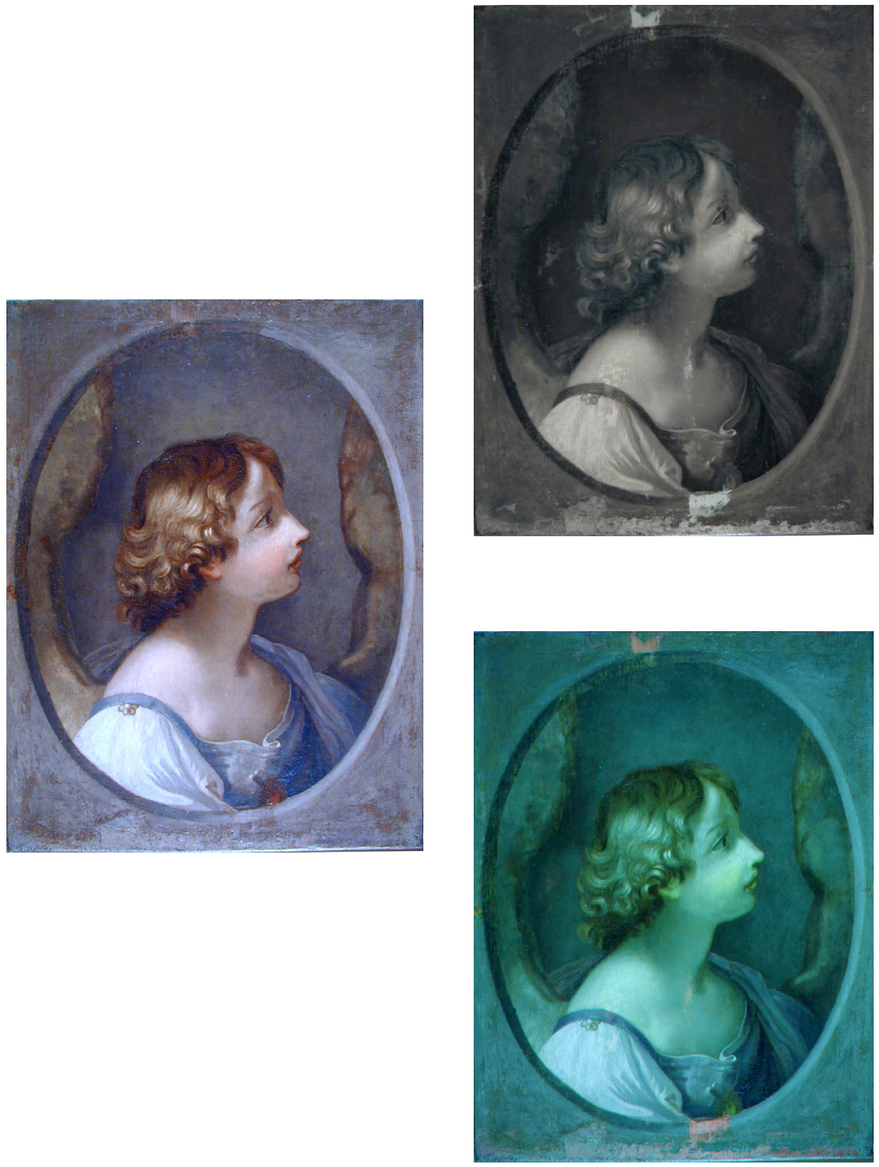



Figure 3.4
Types of raster images. Binary Image

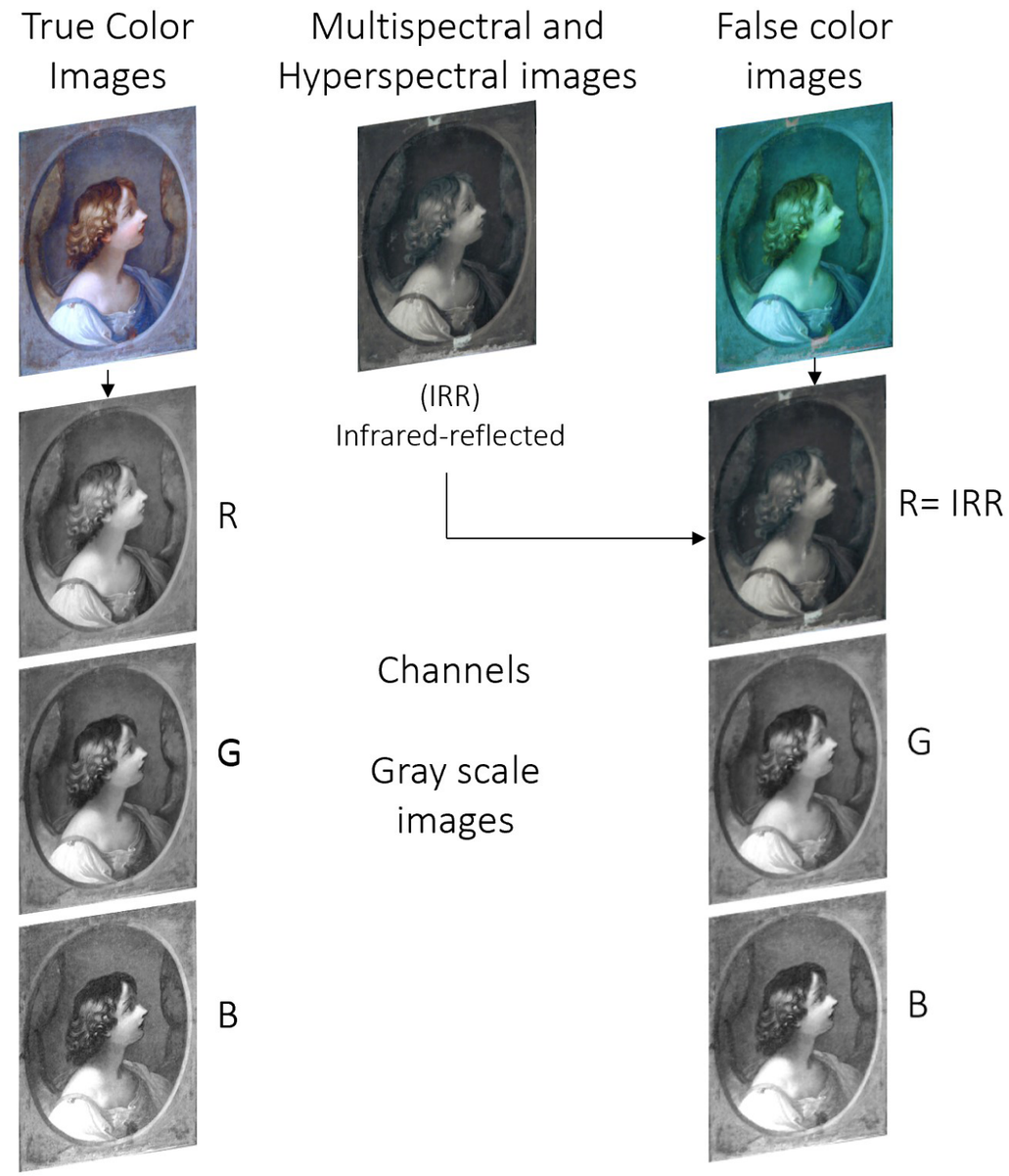
Source: https://it.mathworks.com/help/images/image-types-in-the-toolbox.html

Figure 3.5
Types of raster images. Example of a set of diagnostic images.

Painting on canvas, *Annunciation*, Angel Gabriel, author Unknown, Urbino, (PU)







## 3.1.3 Pixel Relations, Region and Edge Models

Real objects within a digital image are represented by a set of pixels with similar luminous intensity values $f$ and characterized by relations between the pixels such as Adjacency, Connectivity, Regions, and Boundaries. These relations between pixels define the belonging or not of the object's features to specific classes and categories, described in section 1.4 figure 1.14, such as the artifact's executive techniques, previous interventions, etc.

Pixel connectivity is a fundamental concept, simplifying the definition of concepts such as *regions* and *boundaries*. To assess if two pixels are connected, thus belonging to the same category, we must determine if they are close and if their levels satisfy a specific likeness criteria; for example, if their gray levels are the same. To indicate the set of gray level values used to define adjacency, we use $V$.

***In a binary image*** with values 0 and 1, two pixels can be 4 neighbors, but they are said to be connected only if they have the same $V$ value. In a binary image, $V=\{1\}$ if we refer to the adjacency of pixels with value 1.

***In a grayscale image***, the $V$ set typically contains several elements. For example, in the adjacency of pixels with a range of gray level values from 0 to 255, the $V$ set could be any subset of these 256 values.

### 3.1.3.1. Adjacency

Given a pixel $p$ of coordinates $(x,y)$, it has four horizontal and vertical neighbors that have coordinates:

$$(x+1,y),(x-1,y),(x,y+1),(x,y-1) \tag{6}$$

They represent a set defined $N_4(p)$ that is the set of 4-neighbors of pixel $p$. When the 4-neighbors have similar intensity values $V$ we are looking at a subset $S$ that can identify a region $R$, which in our case corresponds to the region of interest (ROI); $V$ represents a group of values used to define the adjacency, in our case corresponding to the values present in the central cell of the array, then the pixel $p$ $(x,y)$.



The 4- neighbors diagonal of $p$ have coordinates

$$(x+1,y+1),(x+1,y-1),(x-1,y+1),(x-1,y-1) \tag{7}$$

and form $N_D(p)$ set.

These points $N_D(p)$, together with the 4-neighbors $N_4(p)$, are called the 8-neighbors of $p$, indicated by $N_8(p)$.

Each pixel is a unit distance from $(x,y)$, and some of $p$ are outside the digital image if $(x,y)$ is at the margin of the image.

| | | |
|---|---|---|
| $(x-1,y-1)$ | $(x,y-1)$ | $(x+1,y-1)$ |
| $(x-1,y)$ | $(x,y)$ | $(x+1,y)$ |
| $(x-1,y+1)$ | $(x,y+1)$ | $(x+1,y+1)$ |

We should consider a total of three types of adjacency:

- *4-adjacency*. Two pixels $p$ and $q$ whit values from $V$ are 4 adjacent if $q$ is in the set $N_4(p)$
- *8-adjacency.* Two pixels $p$ and $q$ whit values from $V$ are adjacent to 8 if $q$ is in the set $N_8(p)$.
- *m-adjacency* (mixed adjacency). Two pixels $p$ and $q$ whit values from $V$ are *m-adjacency* if

  *i.* if pixel $q$ is present in $N_4(p)$ or
  *ii.* if pixel $q$ is present in $N_D(p)$ and the set $N_4(p)\cap N_4(q)$ has no pixels whose values are in $V$.

Mixed adjacency was introduced to eliminate the ambiguities that often occur when using 8-adjacent.

The same reasoning can be applied to the $R$ regions, identifying them as subset $S$ of the image. Two subsets of the $S1$ . and $S2$ are adjacent if some pixels in $S1$ are adjacent to some pixels in $S2$ .

### 3.1.3.2. Connectivity and Regions

Adjacencies between pixels create connections called *paths* (singular *path)*, which can be identified as a sequence of pixels. Given the subset of pixels $S$ . , two pixels $p$ and $q$ are connected in $S$ if there is a path between them composed entirely by pixels belonging to $S$ .

For each pixel $p$ in $S$ , the set of pixels connected to it in $S$ is called a connected component of $S$ . If it has even one connected component, then set $S$ is called a connected set.

Identifying a region $R$ as a subset of pixels in an image; we can call the set $R$ a region of interest ROI of the image if $R$ is a connected set.

Thus, areas of pixels corresponding to researched features in an artifact can be defined with the term ROI *region of interest*, and its adjacency and connectivity properties allow to determine which pixels belong to that region.

Two regions $R_i$ and $R_J$ are called *adjacent* if their union forms a *connected* set. Regions that are not adjacent are called *discontinuous* but can have the same characteristics, identified as $V$ values and, therefore, belong to the same category, classified as a single region of interest ROI.

In addition, regions can be identified as foreground or background. For example, suppose that in an image there are $K$ distinct regions $R_k, k = 1.2\ldots, K$ , we named as $R_u$ the union of all $K$ regions and with $(R_u)^c$ its complementary, i.e. a set that contains all points that are not in $R_u$ . All points in $R_u$ are said in foreground and all points in $(R_u)^c$ are said in background (Fig.3-6).



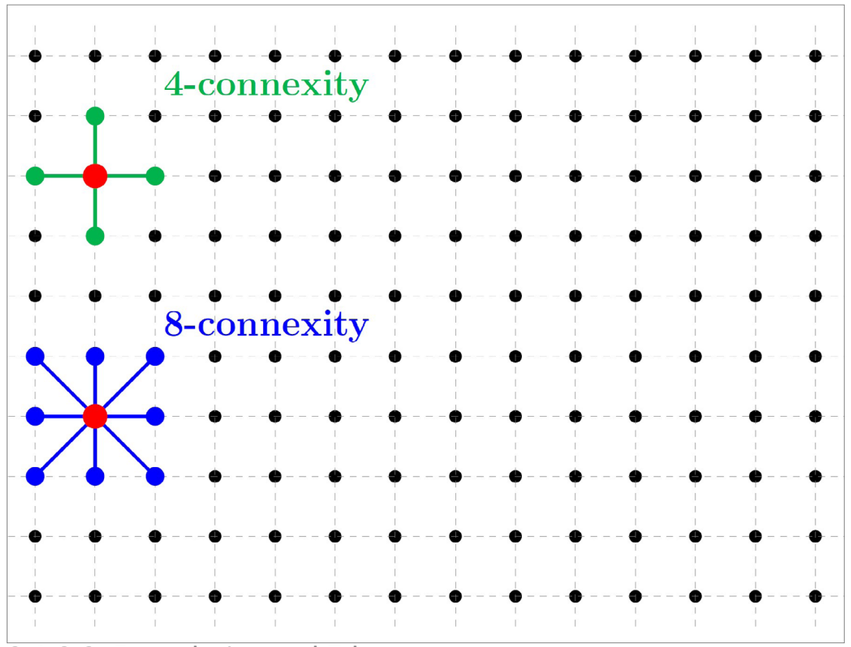



Figure 3.6
Connectivity scheme between pixels

### 3.1.3.3. Boundaries and Edges

A *boundary* (also called *border* or *contour*) of an $R_u$ region is the set of pixels adjacent to the complementary region $(R_u)^c$ . So, the boundary consists of a set of pixels that have at least one neighboring pixel in the background. Usually the boundary is calculated in terms of *8-adjacency,* and inside the boundary we can distinguish two limits, an *inner limit* and an *outer limit*; the latter corresponding to the adjacent pixels in the background.

It is essential to distinguish between the concepts of *boundary* and *edge:*

*i.Boundary* is a *global* concept, common to all sides of a region of interest and can be identified as a line of pixels enclosing a region and forming a closed *path*. As previously declared *"restoration documentation of any artifact requires a series of non-illustrative, non-raster vector drawings, i.e., without shadings and with topographically coherent closed polygons",* so in our case the boundary corresponds to the border of the *vectorial polygon,* clearly defining a specific region of the artifact.

*ii. Edges* are local intensity variations present among the pixels defining *internal* and *external limits* of a region, usually characterized by strong or subtle discontinuities between gray levels. By defining a $V$ value as threshold it's possible to obtain *edges* connected to each other which correspond almost completely to the global *boundary*.

*iii.*The only exception in which *edges* and *boundary* correspond is in binary images.

We can define three main models of edges depending on their intensity contours.

***a. Step Edge***

A step edge implies a sharp transition between two intensity levels which happens ideally at a distance of one pixel or less.

In cultural heritage images which present this typology of edge, objects in the foreground stand out sharply from the background. For example, images of manuscripts or drawings are very close to this kind of edge as they are characterized by a text which usually stands out from the background both for its intensity level and for its constitutive material: ink or graphite on Paper or Parchment. (Fig.3.7-9) For this reason, identifying the outline of a text or the lines of a drawing is often easy to do, in almost all case studies.

On the side of diagnostic photography, we find models of step edge in radiographic images of wooden artifacts such as sculptures or painted boards, metallic artifacts or chalks. In fact, radiographic images are distinguished by strong contrasts between the elements which compose the object.

Step edges can also be created while taking photos in visible light, for example a crucial indication to be followed during documentation procedure is exactly to respect this distinction by photographing the artifact against a neutral background: *"Keeping the distinction between main figure and background, i.e., preserving the full readability of the information model and the object model, whose overlapping forms defined graphic documentation".* Photographs taken in visible light before and after conservation intervention can respect such characteristics of distinction between the main figure and the background. In these cases, it will be easy to identify the foreground object's silhouette.



***b. Edge with ramp intensity profile***

Ramp edges are the most common in all types of digital images, including cultural heritage ones. We can classify different ramp amplitudes, but they all include a soft grading between object and background, or between two contiguous objects. In this case, the difference between intensity levels is given by connected pixel sets or segments, forming a shade. These Edges are also characterized by a blur component-defined mainly by the focus of acquisition devices such as photographic optics – and by a noise component – produced by the sensor's electronic components. The majority of real edge models imply that there is a gradual transition on the ramp.

This kind of ramp has a determinant role in feature extraction, as it isn't simple to determine the threshold to define the single boundary of a region.

***c. Roof Edge***

*Roof Edges* represent intensity intervals similar to an impulse. They are presented in drawings, lines and images with fine details. A line can be seen as an edge segment in which the background intensity on both sides is more or less than the pixels of which the line itself is made. An isolated point can be seen as a line with the length and height of a pixel.

Most of the digital images include all three types of edge, but for features' recognition and extraction the region outlines need to be sufficiently distinct from one another and from the background, so as to allow identification based on discontinuity of local intensities. In certain situations, it's possible to take into account contour conditions, as known in advance, as with neutral backgrounds, or with a paper or parchment background, or even in the case of radiographic images; in all other cases, it's necessary to identify some $V$ values which could become threshold points, so as to gain a binary image in which all edges correspond to the region of interest's global contours. The research for a threshold value is a local operation which must be carried out by operators through trial and repetition, until a result appropriate to the extracted features is reached.

Figure 3.7
Ideal rappresentation of edge models.
a) Step Edge
b) Ramp Edge
c) Roof Edge

Source:
Gonzalez, Rafael C., and Richard E. Woods. 2012. Digital Image Processing (2nd Edition). 2nd ed. ed. Marcia J. Horton. New Jersey: Prentice Hall.

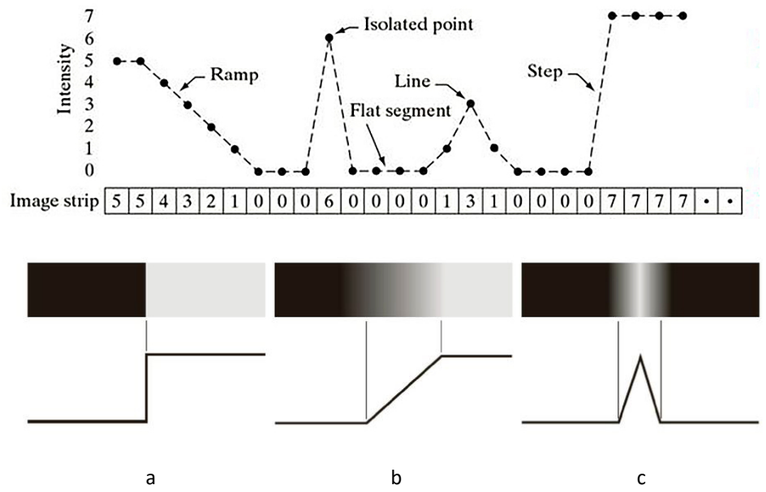



Figure 3.8
Radiograph of a ligneous statue.
The stepped edges of the nails are highlighted.







Figure 3.9
Example of Manuscript. Image in visible light on homogeneous background. Stepped edges present between background and artifact and between ink letters and scroll.





Figure 3.10
Example of a painting on canvas characterized by Ramp Edge

## 3.1.4 Color spaces and segmentation

Use of color in image elaboration is crucially important as it can simplify identification of an object and its extraction from a scene, providing more information than the gray levels. In fact, the human eye is able to recognize thousands of color and intensity gradations, compared to just two dozen tones of gray, which represents a crucial characteristic in the manual analysis of an image. We can identify two forms (or models) of human color vision, the first corresponding to biological color processing in the human visual system, the second corresponding to physiology of vision, i.e. the perception of color from a psychological or psychophysical point of view. Characteristics which are generally considered in both visual forms to recognize colors are *brightness, hue* and *saturation;* the table shows how these features take on different meanings according to the form of vision.

Table 3.1
Different meanings of color characteristics depending on the form of vision.

| | **Physiological Models**<br>**Biological color processing in the human visual system** | **Psychological Models**<br>**Psychological or psychophysical perception of color** |
|---|---|---|
| ***Brightness*** | Brightness includes the notion of luminous intensity $f$ | Value that measures the apparent *brilliance* of a visual stimulus, alone or in its context. |
| ***Hue*** | Attribute associated with the dominant wavelength in the set of incident light waves. Therefore it corresponds to the "color" of the object. | Value that indicates the ability to distinguish equally brilliant areas or with the same texture. Corresponds to the intuitive concept of color. |
| ***Saturation*** | It refers to purity, i.e. the amount of white light mixed with a given hue. Pure colors in the spectrum are completely saturated. | Value that indicates how pure the color is perceived, i.e., how much it differs from the gray. |
| ***Chromaticity*** | The combination of hue and saturation is called *chromaticity*, so a color can also be characterized by its brightness and chromaticity. | |



*Physiological models* refer to biological color processing in the human visual system and are based on the theory trichromatic spectral elements combination *(tristimulus values*) formulated by Young in the early 1800s, according to which, starting from three independent light sources, said primary colors, it's possible to obtain any other color through appropriate *color matching*. Combining and adjusting the luminous intensities of three rays of light corresponding to the blue, red and green specters, all colors perceivable by the human eye can be synthetized tutti; for this reason, color generation through the RGB model is called additive synthesis. The quantity of red, green and blue needed to form a given color is said *stimulus value* and is indicated respectively with X, Y and Z. Thus, color is specified and defined through three *trichromatic values* defined as[1]

$$x = \frac{X}{X+Y+Z}$$

$$x = \frac{Y}{X+Y+Z} \qquad (8)$$

$$z = \frac{Z}{X+Y+Z}$$

From these equations comes that

$$x + y + z = 1 \qquad (9)$$

To reach a standardized color description, the *Commission International de l'Eclairage* (CIE) (or International Commission on Illumination) standardized in 1931 an XYZ triplet of hyper-saturated primary colors, not physically existent but defined so that all visible colors could be obtained through an additive blend of these. Furthermore, starting from three specific pure tones corresponding to 435.8, 546.1 and 700 nm wavelengths, the CIE defined a *chromaticity diagram* formed by physically reachable primary colors. The diagram shows the color composition as a function of $x$ (red) and $y$ (green). For each value of $x$ and $y$ the corresponding value $z$ (blue) is obtained from the equation $x + y + z = 1$ assigning $z = 1 - (x + y)$. Furthermore, combinations of "virtual" primaries are possible, producing not visible (or nonexistent) colors, corresponding to points beyond the diagram area.

1 The use of  and  in this case follows the conventional notation and should not be confused with the use of  to indicate spatial coordinates of the points sampled by the sensor, corresponding to the image array pixels.

Chromaticity diagram is a useful tool to define colors, but it doesn't correspond to the way in which hardware operates color vision, nor to human vision. For digital vision and for printing, colors are commonly represented as points in a tridimensional space and the geometric models in which they are placed are called *color spaces*. Thus, a digital color space is a mathematical representation of our visual perception, in which three attributions are used to describe a color.
Color spaces are based on the two listed forms of vision, i.e. on the physiologic and psychologic models.

*i. Physiological models* are linked to ophthalmology and oculist studies on the anatomy and structure of our sensorial organs, the eyes. These models, considering there are three different types of cones in the retina, refer to a vectorial space with tridimensional base. XYZ and RGB models described below belong to this category. Furthermore, these models are also hardware-oriented, meaning they are defined as based on the properties of color representing optical tools, such as screens or printers. This category includes RGB, CMY, YUV (which is the standard PAL/European standard for YIQ) spaces.

*ii. Psychological models* are based on how colors are perceived by a human observer, using the reactions of a relevant sample of volunteers. These models are user-oriented, i.e. based on human color perception in terms of hue, saturation and brightness. This category includes HLS, HCV, HSV, HSB and MTM, L*u*v*, L*a*b* y L*C*h*.

As is known, performance of a segmentation procedure carried out on color images depends on the choice of color space, especially if the segmentation is done by hand. It's impossible to universally define an optimal color profile for all segmentation purposes, however it is possible to indicate some color spaces which can be better suited for a specific task. Many authors have tried to identify the most appropriate color spaces for their specific color image segmentation problems, providing contradictory conclusions, as the optimal color space depends on the context and purposes of segmentation. Furthermore, when using any one of the typical color spaces is not enough, new spaces can be composed by selecting a series of color components which may belong to any one of the classic color spaces. Such spaces, whose color significance is neither psycho-visual nor physical, are called hybrid color spaces.



The research proposed in this dissertation was mainly devoted to grayscale channel analysis, however in some case studies this procedure did not yield the desired results. For this reason, tests have been carried out on a few hybrid color spaces. In this section, we will consider RGB color space as it represents the starting space used to carry out linear or non-linear transformations and obtain other kinds of color representation. Canonic HSV, L*a*b* spaces will be described, as they have stood out as useful to color segmentation in tested case studies. The experimented hybrid color space will be treated in section 5.3.2.

#### 3.1.4.1 RGB

RGB space can be described mathematically with a Cartesian coordinate system forming a data cube with one unit side. Colors are represented as points inside the cube and are defined by vector coordinates and discrete values ranging from 0-corresponding to black- to 255-corresponding to white- as shown in the figure 3.11. In the RGB system, colors are obtained by adding three primary colors: red (R), green (G) and blue (B). The tristimulus values can be obtained from RGB coordinates using the following three simple linear relationships:

$$\begin{aligned} X &= 0.490\,R + 0.310\,G + 0.200\,B \\ Y &= 0.177\,R + 0.831\,G + 0.010\,B \\ Z &= 0.000\,R + 0.010\,G + 0.990\,B \end{aligned} \tag{10}$$

white is represented as $X = 1,\ Y = 1,\ Z = 1$;
black is represented as $X = 255,\ Y = 255,\ Z = 255$.
This is the model most widely used by acquisition, representation and visualization of digital images hardware in electronic systems. Although RGB space corresponds to biological color processing in the human visual system, it is not related to perception from a psychological or psychophysical aspect. However, in this paper [103] the authors formulate a projection of RGB vectors within the RGB color space to separate achromatic and chromatic information. This color space was not adequate for artifacts image analysis, so it was converted to other color spaces using linear combinations with a fixed coefficient.

### 3.1.4.2 HVS

The HSV model corresponds to Hue, Saturation, Value, and derives from the approximation model of Albert H. Munsell, who conducted studies on color perception at the beginning of the twentieth century. This model is based on subjective observations and not on the direct measurement of hue, saturation and brightness [104]. The main model derived from Munsell's model approximation is the HIS (Hue, Intensity, Saturation) model from which other models are derived: HIS (Hue, Chroma, Value), HSV (Hue, Saturation, Value), and HSB (Hue, Saturation, Brightness). These models support an intuitive notion of color that separates brightness from other components. In the HSV color space, hue (H) represents the shade of color (e.g., red or blue), saturation (S) is the quantity of color (e.g., bright red or light red), and the third component (called intensity, value, or brightness) is the quantity of light, allowing to discriminate between dark and light colors.
In this space, hue is represented as a three-dimensional conical shape of the color circle. Saturation is represented by distance from the center of a circular cross-section of the cone, and value is the distance from the pointed end of the cone. The cone's main axis represents the grayscale line (Fig.3.11).
For HSV system, relationship with the RGB model is expressed by the following relations:

$$V = 1/3\left(R+G+B\right)$$

$$S = 1-\frac{3}{R+G+B}\min\left(R,G,B\right)$$

$$H = 180\frac{0,5\left(R-G\right)+\left(R-B\right)}{\left(\left(R-G\right)^{2}+\left(R-B\right)\left(G-B\right)\right)^{1/2}} \; if \; S \neq 0 \qquad (11)$$

$$H = undefined \; if \; S = 0$$

$$H = 360 - H \;\; if \;\; \frac{B}{V} > \frac{G}{V}$$

HSV color components can be derived from RGB or XYZ models by linear or non-linear transformations. This model is very useful for color segmentation in complex contexts such as artistic artifacts' images. The main reason for this usefulness is in V's components, i.e., in the values corresponding to brightness gradations, which allow to detect even the slightest variations in light intensity, and



therefore the smallest discontinuities between areas of interest. Color properties thus described have an immediate perceptive interpretation by restorers, who are accustomed to distinguishing colors according to their visual perception, on which this model is based. Some results are shown in the case study Madonna with child in section 5.3.

### 3.1.4.3 L*a*b*

In the L*a*b* color space, color differences perceived by humans are approximated by a Euclidean distance. Quantities L*, a* and b* are obtained from a non-linear transformation of the XYZ or RGB tristimulus values. L* stands for Luminance and a and b are the chromaticity coordinates describing red/green and blue/yellow, respectively. Luminance extends from 0 (dark) to 100 (light), the a* component ranges from-120 (red) to +120 (green) and the b* component ranges from +120 (yellow) to-120 (blue). L* brightness is based on perceptive measures of brightness and not real physical values. The CIE recommends its use for comparing colors in scenes illuminated by daylight; in the segmentation process, it performs similarly to the HSV color space. RGB tristimulus values can be converted to L*a*b* coordinates using the following relationships:

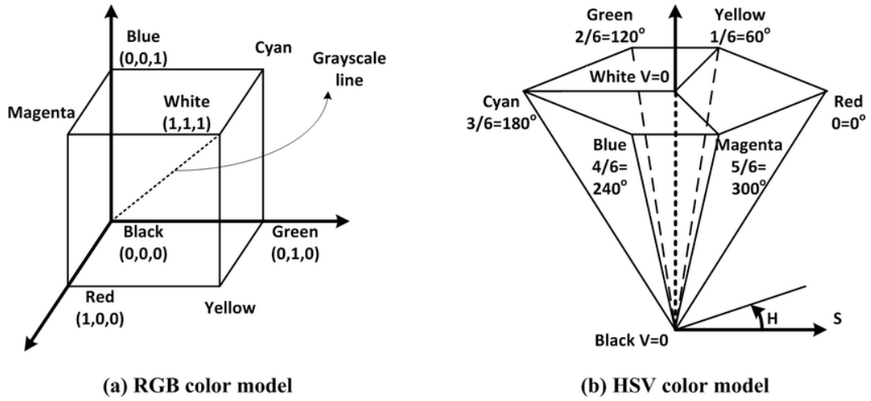
$$\begin{aligned} L^* &= 116(Y/Y_o)^{1/3} - 16 && \text{to } Y/Y_o > 0.008856 \\ L^* &= 903(Y/Y_o) && \text{to } Y/Y_o \leq 0.008856 \\ a^* &= 500\,(f(X/X_o) - f(Y/Y_o)) \\ b^* &= 200\,(f(Y/Y_o) - f(Z/Z_o)) \end{aligned} \qquad (12)$$

where $X_o, Y_o, Z_o$ are the white reference values,
Y is the illumination value that the human eye recognizes as white light and

$$\begin{aligned} f(t) &= (t)^{1/3} && \text{to } t > 0.008856 \\ f(t) &= 7.787t + 16/113 && \text{to } t \leq 0.008856. \end{aligned} \qquad (13)$$

L*a*b* is important for the cultural heritage sector because it can be used as a reference color space to convert a color from one space to another predictively. L*a*b* was developed specifically to operate independently from hardware, i.e., to manage colors independently from the used devices (i.e. monitors, printers, or computers) and is therefore very useful in obtaining true and expected results in print.

Figure 3.11
RGB and HSV color space.




**(a) RGB color model** **(b) HSV color model**

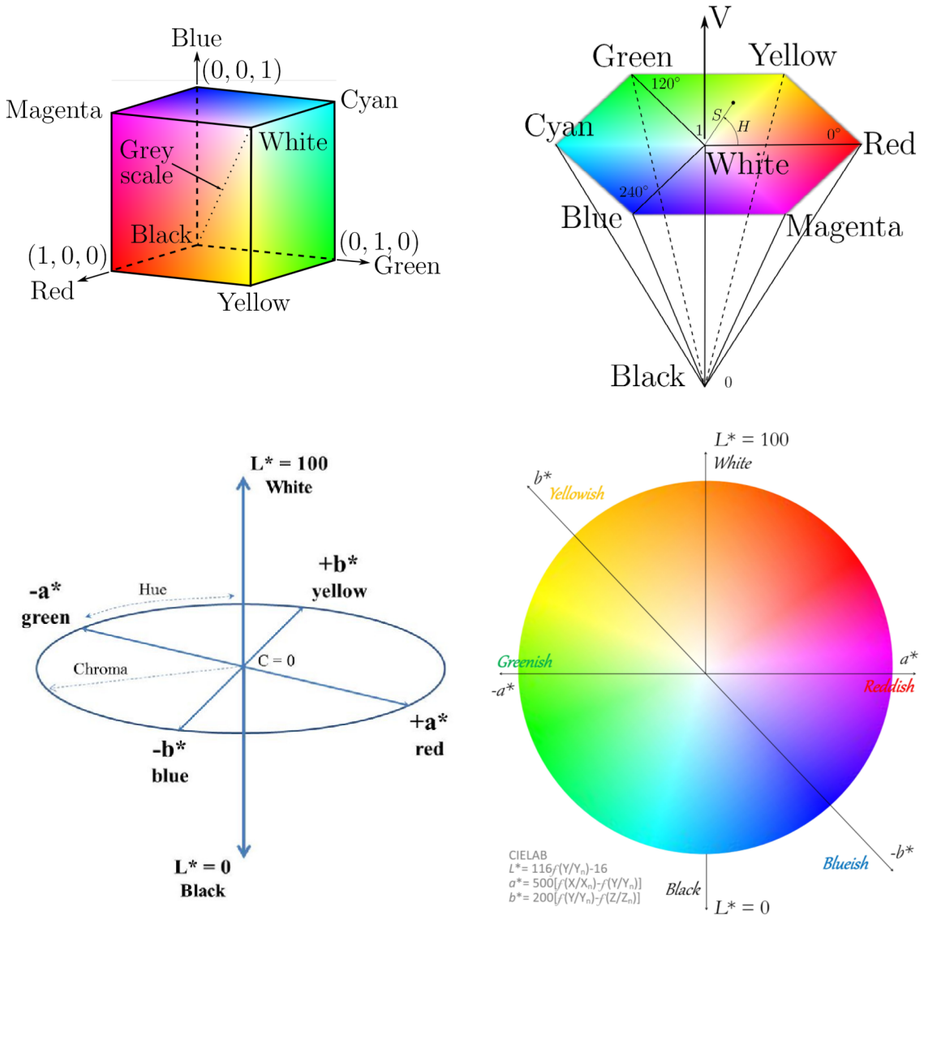



Figure 3.12
L*a*b* color space.

## Section 3.2 Image Analysis Algorithms

Image analysis is a process intermediate between image processing and computer vision. We can consider three types of processes respectively of low, medium and high level.

***Low-level processes:*** involve basic operations in the processing and treatment of images. This category belongs to all the processes of optimizing the readability of images, such as reducing noise, increasing contrast or sharpness, and decreasing pixel values to two binary classes. In these processes, both input and output data are images.

***Mid-level processes include*** segmentation techniques-dividing images into regions or objects-, separation techniques-which can be interpreted as segmentation-soft-and optimization of extracted regions. In this case, the input data are generally images while the output data are attributes extracted from the images themselves, e.g., features, ROI regions of interest, edges.

The segmentation process is intended to decompose an image domain in distinct regions on the basis of characterizing features extracted from the image itself, such as gray level, color, texture, or shape details.

In other words, segmenting an image is tantamount to find a partition of its domain $\mathrm{D}$

$$D = \bigcup_i R_i \qquad R_i \cap R_j = \varnothing \; \forall i \neq j \tag{14}$$

that is, finding a number of regions $R_i$ that cover entirely the image domain, do not overlap and are characterized by different properties, homogeneous within each region, in terms of the image features considered. The fact that the intersection area is required to be empty by Eq. (14) motivates this process to be called *hard* segmentation: assuming a pixelated image, each pixel belongs to one and only one region.

Denoting by F(p) a scalar or vector-valued image defined on D and by p a generic pixel in D, an equivalent definition of the partition in (14) is the following

$$F(p) = \sum_i F(p) \times I_{R_i}(p) \tag{15}$$

where $I_{R_i}$ is the indicator function of region $R_i$, that is

$$I_{R_i}(p) = \begin{cases} 1 & if \; p \in R_i \\ 0 & otherwise \end{cases} \tag{16}$$

An alternative way to interpret the segmentation process is to find a set of scalar or vector-valued *source* functions $s_i$, based again on characteristic properties of the *observed* image F, such that

$$F(p) = \sum_i a_i s_i(p) \tag{17}$$

that is, F results from a linear combination of functions $s_i$. The fundamental difference between this relation and Eq. (15) is that all the $s_i$ are defined over the whole D. Equation (4) is exactly a hard segmentation only if each $s_i$ is everywhere zero outside some region $R_i$. In other cases, when $s_i$ can assume (small) nonzero values outside $R_i$, Eq. (17) can be considered a *soft* segmentation, in the sense that different segments can overlap with each other.

Source separation techniques, in particular, *blind* source separation techniques, treated in section 3.2.1, can often reach a sort of soft segmentation of a vector-valued image.

For reasons made explicit below, when dealing with multispectral images of historical-artistic interest within the scope of this thesis, applying separation strategies rather than hard segmentation is often more convenient to extract the regions of interest. Indeed, an artwork's graphic documentation does not need a complete partition of the image domain, but to select a limited number of regions characterized by homogeneous spectral signatures. These can be obtained easily by thresholding some source functions, which can only be chosen by individual

experts based on either the required spectral features or some direct knowledge of the physical artifact being studied.
These publications [105],[106],[107]image semantic segmentation is an important research branch and it is also a challenging task. Applications such as autonomous driving, Unmanned Aerial Vehicle System (UAVS are investigated the main algorithms for low and medium level image analysis.

***High-level processes:*** they intend to attribute semantics to a set of objects with homogeneous characteristics, implementing the cognitive functions normally associated with human vision. These processes include supervised or unsupervised classification and Deep Learning algorithms. In this survey [108] it's provide a comprehensive review of the literature at the time of this writing, covering a broad spectrum of pioneering works for semantic and instance-level segmentation, including fully convolutional pixel-labeling networks, encoder-decoder architectures, multi-scale and pyramid based approaches, recurrent networks, visual attention models, and generative models in adversarial settings. We investigate the similarity, strengths and challenges of these deep learning models, examine the most widely used datasets, report performances, and discuss promising future research directions in this area.
The high-level processes related to supervised and unsupervised area classification are not efficient for the purposes of this research. Regarding unsupervised classification, pixel values, shape and orientation of regions cannot be considered as a basis for classification.
Supervised classification also presents substantial limitations; in most cases, it is impossible to identify homogeneous areas to use as training because they are not known a priori. Moreover, this approach's major problems arise if overlaps between classes are present or if some pixels fall outside the chosen homogeneous group. These two phenomena lead to a high probability of error in classification or to a large number of unclassified pixels. For these reasons, the classification's operations and, therefore, semantic attribution of the extracted regions are assigned to the restorer operator's full control.
In the following sections, we analyze some low and medium-level algorithms useful for methodological purposes, with particular attention to the processes of separation, optimization and feature extraction in regions of interest (ROI). These are presented in a sequential order that has proved efficient in performing a correct analysis of the image with consequent vector extraction of interest areas.



## 3.2.1 Blind Source Separation BSS

BSS Blind Source Separation techniques are included in the mid-level analysis processes and are based on Independent Component Analysis and second-order statistics.

Considering the visible light or multispectral images of an artifact - more or less degraded- as a set of multivariate data, BSS techniques allow optimizing these data's structure by extracting the regions of interest sequentially from a set of their mixtures, making them more visible and understandable. The data set we consider are the components of the local reflectance values of materials, acquired in all available channels and recorded in individual pixels. Unfortunately, material reflectance values typically overlap in all channels since most materials are mixed and layered with each other. This aspect often makes it challenging to recognize ROIs and can mask or make the reflectance phenomenon of some material layers invisible. This problem can be approached with some unsupervised separation techniques, able to learn from the data itself how to separate and highlight regions without any external input.
Mathematically, this would be easily possible if the spectral emissions of different materials were known, but this is rarely the case. In order to extract the different regions from multispectral data without knowing their spectra, it is necessary to make some assumptions about the regions themselves and the mixing mechanism that produces their spectral appearance. Suppose that each pixel (of index $t$ in a total of $T$ ) of visible light or multispectral image of an artifact has a vector value $x(t)$ of $N$ components. Similarly, let us assume to have $M$ overlaid sources represented, at each pixel $t$, by the vector $s(t)$. Since we consider images of artifacts containing homogeneous regions of interest, we can also reasonably assume that the color of each source is almost uniform, i.e., we will have mean reflectance indices $Aij$ for the $i-th$ source at the $j-th$ wavelength. Thus, we will have a collection of $T$ samples from a random $N$ -vector $x$, which is generat-

ed by linearly and instantaneously mixing the components of a random $M$ -vector $s$ through an $N \times M$ mixing matrix $A$ :

$$x(t) = As(t) \qquad t = 1,2, ...,T \tag{18}$$

where the source functions $s_i(t), i = 1,2, ...,M$ denote the "quantity" of the $M$ patterns that concur to form the color at the point $t$ .

This model is also called *instantaneous* because the data values at each pixel depend only on the feature values at that pixel and not on any neighborhood of it. If we can extract the map from the data , it will be easy to extract the regions related to the feature $j-th$ by simply locating the regions where $s_j(t)$ takes on significant values. Extracting $s_j(t)$ from $x_i(t)$ without any knowledge of $A_{ij}$, is a blind source separation problem (BSS), which can only be solved with additional assumptions on $s_j$. Statistical techniques of BSSs such as *principal component analysis* (PCA) [109] and independent component analysis (ICA) [110] work on the data by assuming that different features of $s_j$ have some degree of statistical independence from each other. The data analyzed by ICA could come from many different types of application fields, including digital images, document databases, economic indicators, and psychometric measures. In many cases, measures are provided as a mixture of parallel signals or time series. Typical examples are mixtures of simultaneous speech signals that have been picked up by several microphones, brain waves recorded by multiple sensors, interfering radio signals arriving at a cell phone, or parallel time series obtained from some industrial process. In specific, the FastICA algorithm is a popular algorithm for independent component analysis, developed by Aapo Hyvärinen at Helsinki University of Technology. The algorithm is based on a fixed-point iterative scheme to maximize the non-Gaussianity of a statistical measure of independence. The algorithm can also be derived from Newton's approximate iteration. FastICA is a highly computationally efficient method for performing ICA estimation. It uses a fixed-point iteration scheme that has been found in independent experiments to be 10-100 times faster than conventional gradient descent methods for ICA. Another advantage of the FastICA algorithm is that it can also be used to perform projection search, thus providing a general-purpose data analysis method that can be used both exploratory and for independent component (or source) estimation. Here are some



publications on the algorithm [111],[112]as well as in many other disciplines, is finding a suitable representation of multivariate data, i.e. random vectors. For reasons of computational and conceptual simplicity, the representation is often sought as a linear transformation of the original data. In other words, each component of the representation is a linear combination of the original variables. Well-known linear transformation methods include principal component analysis, factor analysis, and projection pursuit. Independent component analysis (ICA . These techniques have proven to be powerful tools for exploiting the spectral diversity of patterns contained in multispectral images of artworks, thus allowing the detection of hidden details or the removal of unwanted interferences [113], [114], [115]. Since each output map assumes significant values only where a single feature is present, the ROIs characterized by such a feature can be extracted by just distinguishing between foreground and background. In fact, at best, two primary gray levels dominate each output channel, and only a specific ROI is highlighted. All pixels in the ROI will have similar gray values, and the rest of the image will get confused in the background.

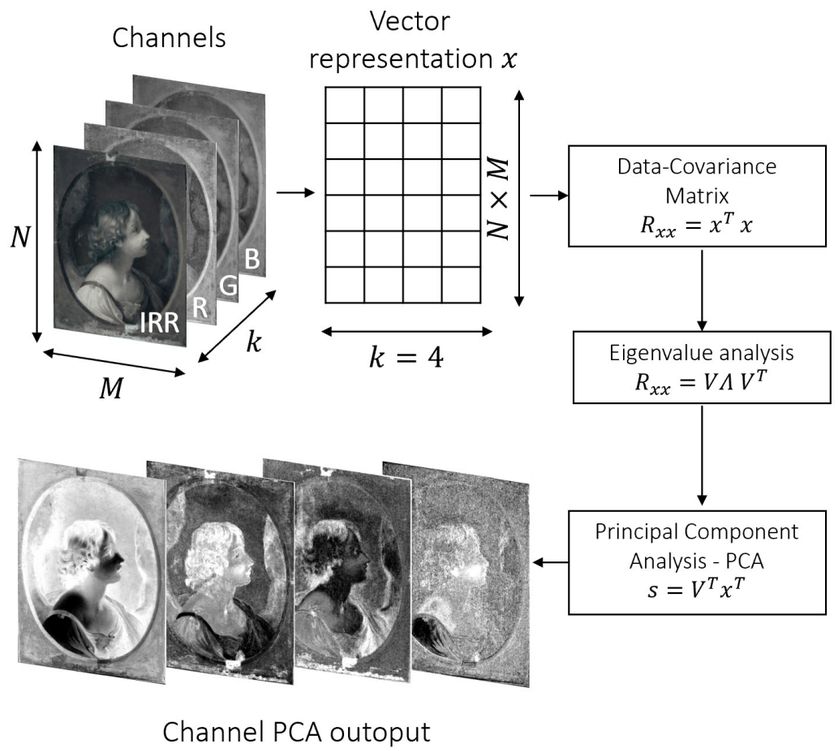



Figure 3.13
Scheme of Principal Component Analysis PCA applied to Image in visible light and multispectral.

Painting on canvas, *Annunciation*, Angel Gabriel, author Unknown, Urbino, (PU)

### 3.2.1.1 Pseudocolor

This section describes an experimental approach to use only "color" uniformity as a criterion for dividing the image into disjoint regions of interest corresponding to distinguishable features on the surface of the artifact. Starting from the assumption that the pixels constituting the significant ROI regions of an image share the same chromatic (or spectral) features, we try to address the segmentation problem on color images by considering it in terms of classifying pixels that are correlated and de-correlated with each other. Instead of looking for the best classical color space, we propose creating a pseudocolor space, organized to obtain the best discrimination between pixel classes. This space cannot be constructed by means of a mathematical model based on a supervised sequential feature selection scheme, as described in this paper[116], since the features in most real case studies are not known a priori.

The new space can be composed by assuming three of the BSS algorithms' outputs as color channels. These channels are generated differently with each application, adaptive with respect to the image being processed, and have no psycho-visual or physical color meaning. For this reason, we will say that images composed with this method have an adapted color space and can be defined as pseudocolor images. The size of the adapted color space is always equal to three as for classical color spaces; the difference is that more channels can be combined using - or joining- more than three BSS outputs in order to produce images with the highest discriminatory rate between the sought-after features. This organization of the channels is appropriate to perform extensive experiments with a high number of images of artifacts, since each artifact presents its own conservation history which, in addition to its peculiarities inherent to the execution techniques, the materials used and the types of degradation, makes it unique. Since it would be very time consuming to evaluate the discriminating power of all possible combinations of color components, channels should be selected in which the regions of interest are already highly discriminated by constant intensity and texture. In this paper [117] the approach just described was used to highlight overwritten text in a palimpsest, showing that satisfactory results can be obtained with this method of color decorrelation even starting from visible light images, results that can often be as highly discriminative as those provided by diagnostic and multispectral images.



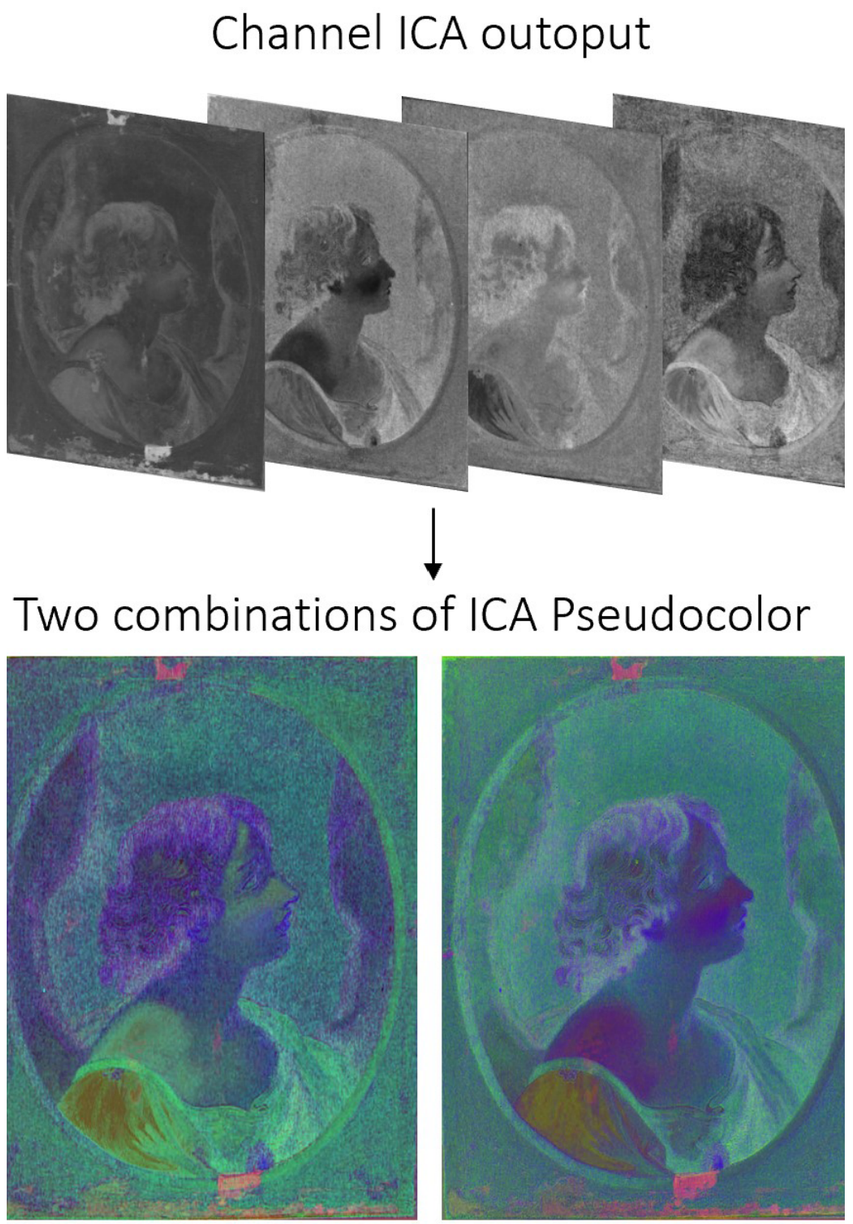



Figure 3.14
Example of pseudocolor with BSS outputs

Painting on canvas, *Annunciation*, Angel Gabriel, author Unknown, Urbino, (PU)

## 3.2.2 Binarization

As mentioned, the Binarization process classifies a $n$ number of discrete values into only two groups of values corresponding to 0-1. Since the purpose of the methodology is to obtain a precise vector drawing for each classified ROI, the Binarization process allows eliminating the overabundance of information caused by the average gray levels, which cause the typical ramp edges between the area of interest and the background. Gradients, in this case, can be classified as noise that slows down and complicates the process of identifying ROIs. In order to further segment the ROIs from the background and perform the binarization process, we use a recursive thresholding algorithm. [118], [119]. Threshold technique is one of the important techniques in image segmentation and can be expressed as:

$$T = T[x, y, p(x, y), f(x, y)] \tag{19}$$

Where $T$ is the threshold value; $x, y$ are the coordinates of the threshold value point; $p(x, y)$, $f(x, y)$ are points the gray level image pixels. Threshold image g(x,y) can be defined:

$$g(x, y) = \begin{cases} 1, & \text{if } f(x, y) \geq T \\ 0, & \text{if } f(x, y) < T \end{cases} \tag{20}$$

Given grayscale channels output from BSS algorithms- which correspond to images $f(x, y)$ in grayscale- a gray gradation is fixed, called intensity threshold $T$. In the binary output image, the pixels labeled with 1 are called object points, while those set to 0 are the background points. The threshold can be applied to the image through three techniques:

***Global techniques*** segment an image based on information obtains globally, e.g., by using image histogram; global texture properties. In the Global threshold, a single threshold value is used in the whole image.

***Local techniques*** are based on the local properties of the pixels and their neighborhoods. The Local threshold is defined as *adaptive* and is assigned to each pixel to determine whether it belongs to the foreground or the background pixel.



***Split, merge and growing techniques*** use both the notions of homogeneity and geometrical proximity in order to obtain good segmentation results.

The result is strongly influenced by choice of the $T$ threshold, which can be defined with different techniques:

***Mean Technique:*** this technique uses an average pixel value as a threshold value. It is very useful in cases where about half of the pixels belong to the objects and the other half to the background. In the case of images of artifacts, this rarely occurs but was very functional applied to the output channels of the BSS ICA and PCA algorithms.

***P-Tile Technique:*** This technique requires knowledge of the area or size of the objects in the image. It also assumes that the objects in an image are brighter than the background and occupy a fixed percentage P% of the overall image area. The threshold is defined as the gray level that mostly corresponds to the mapping of at least P% of the gray level in the object. This technique can be used in rare cases in the cultural heritage sector. For example, on mosaics or contemporary paintings that include limited elements. It is obviously not applicable if the area ratio of the object is unknown or varies from one image to another, and on figurative elements that contain nuances.

***Histogram Dependent Technique (HDT):*** is a technique based on reading the histogram of the image, i.e., the distribution of grayscale intensity values. Regions with uniform intensities give rise to strong peaks in the histogram and the valley points separating these regions can be used as a threshold value to separate objects. In general, an acceptable threshold can be selected if the histogram peaks are tall, narrow, symmetric, and separated by deep valleys. The (HDT) is very suitable for images containing a group of homogeneous areas or with similar intensity values and a homogeneous group identified as background. Also, this technique was very functional applied to the output channels of the BSS ICA and PCA algorithms.

- ***Hysteresis thresholding:*** if there is no clear valley in the histogram of an image, it means that there are several background pixels that have similar gray level value with object pixels and vice versa. Hystreresis thresholding (i.e., two thresholds, one at each side of the valley) can be used in this case. Pixels above the high threshold are classified as object and below the low threshold as background. Pixels between the low and high thresholds are classified as an object only if they are adjacent to other object pixels.

This paper [120] presents a survey of thresholding techniques and an attempt to evaluate the performance of some automatic global thresholding methods using the criterion functions such as uniformity and shape measures. The evaluation is based on some real-world images.

This study [121] investigating the performance of fifteen automatic thresholding methods, namely Huang and Wang's fuzzy thresholding method; inter-mode thresholding method; iso data thresholding method, Li and Tam's thresholding method; maximum entropy thresholding method; mean thresholding method; minimum error thresholding method; minimum thresholding method; moment-preserving thresholding method; Otsu's thresholding method; percentile (p-tile) thresholding method; Renyi's entropy thresholding method; Shanbhag's thresholding method; triangle thresholding method and Yen's thresholding method. In the case studies tested, the threshold was applied on the grayscale channels exiting the ICA and PCA algorithms. The best technique resulted in the local application with the $T$ value selected with the average or HDT.

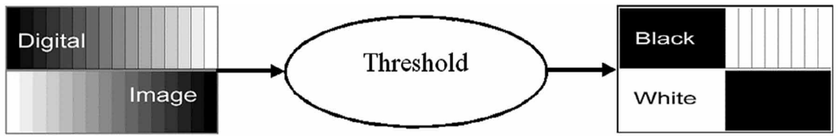



Figure 3.15
General example of thresholding.



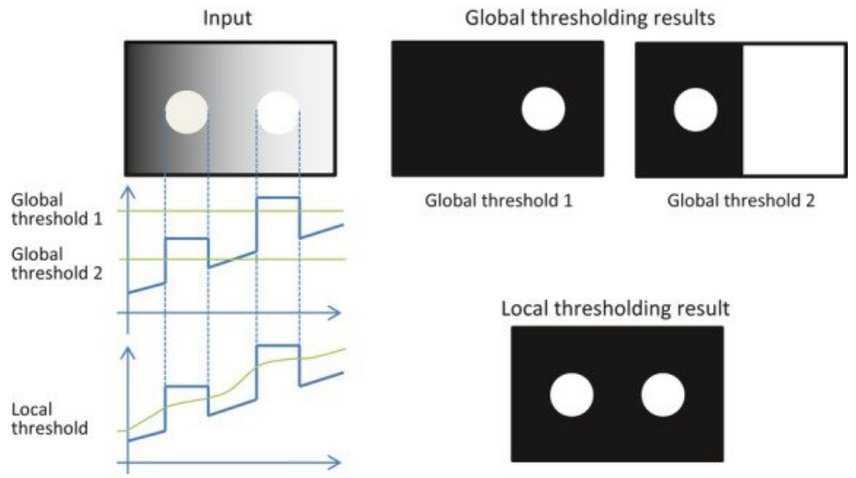



Figure 3.16
Binarization by global thresholding and local thresholding. For this input image, no global threshold provides the result where two circles are successfully extracted. In contrast, the local threshold determined at each pixel by the local average around the pixel will provide a successful result.

Source:
Uchida, Seiichi. (2013). Image processing and recognition for biological images. Development, growth & differentiation. 55. 10.1111/dgd.12054.

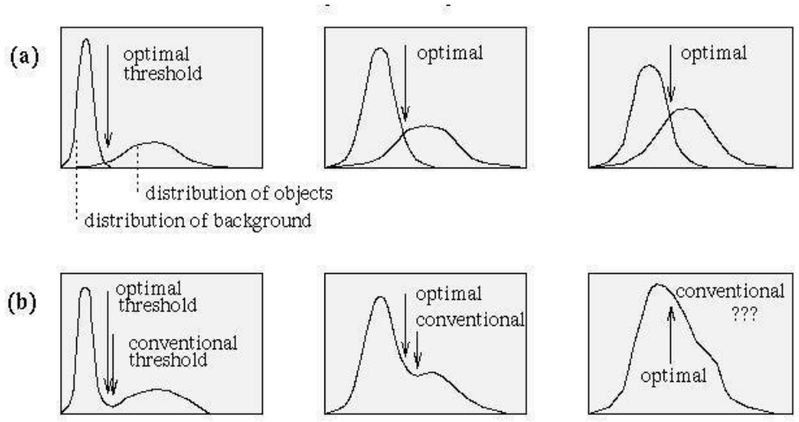



Figure 3.17
Grey level histograms approximated by two normal distributions; The threshold is set to give minimum probability of segmentation error: (a) probability distribution of background and objects, (b) corresponding histogram and optimal threshold.

Source:
Kumar, G V S & .R, Vijaya Kumar. (2014). REVIEW ON IMAGE SEGMENTATION TECHNIQUES. International Journal of Scientific Research Engineering & Technology (IJSRET). 3. 992-997.

## 3.2.3 Morphological Operations

Mathematical morphology denotes a branch of biology that deals with animal's and plants' forms and structures; it has been formalized since the 1960s by Georges Matheron and Jean Serra for studying geometric and milling properties of ores [122]. It aims to analyze the shapes and forms of objects and in the image analysis process, it is used as a tool for extracting image attributes and features useful in the representation and description of object shapes. The mathematical morphology techniques are based on set theory and have always received a great deal of attention because it provides a quantitative description of geometric structure and shape and a mathematical description of algebra, topology, probability, and integral geometry [123].

In this section, only morphological operations related to binary images will be discussed. Their application is connected to the segmentation process and is consequential to the extraction of binary masks. Particularly, topology and shape manipulation are the main topics of relevance in the methodology researched. Shape manipulations allow for cleaning regions from undesired pixels; considered as noise, gaps, or other. The operations that result in topographic coherence between regions are essential to obtain optimal performance in the statistical processing performed on the regions. Basically, in the representation of real objects, there can be no overlap between the boundaries; each object has its boundary that must be contiguous to the background or another object's boundary.

### 3.2.3.1 Binary Morphology

As mentioned, in binary images, each picture element is a tuple or a 2-dimensional vector of the $(x,y)$ plane and containing object (or foreground) pixels of value 1 and nonobject (or background) pixels of value 0. We treat the binary image as a set whose elements are composed of all the pixels of value 1. In mathematical morphology, an image is defined as a set of coordinate vectors in the Euclidean space, $E^N$ denote the set of all points $p=(x^1,x^2,\dots,x^N)$ in an $N$-dimensional Euclidean space. Each set $A$ corresponds to a binary image, i.e., an $N$-dimensional composition in black and white, where the point $p$ is black in the binary image if and only if $p \in A$; otherwise, $p$ is white. Morphological operations on



binary images work with Boolean operations where object pixels with value 1 and background pixels with value 0 can be interpreted as true and false, respectively, in truth tables. The primary operators in Boolean logic are AND, OR, and NOT; the truth tables of each logical operation illustrating all the input combinations are shown in figure 3.18-19.

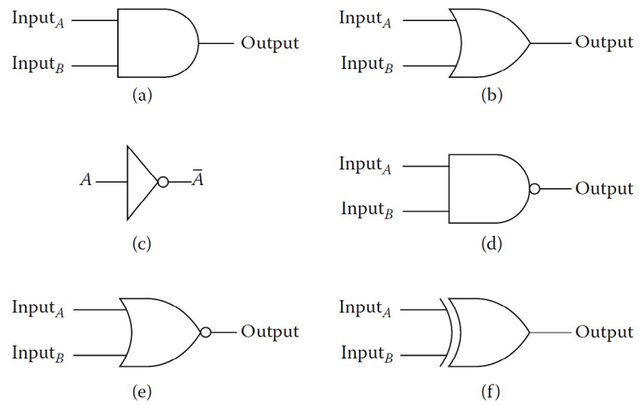



Figure 3.18
The schematic symbols used in circuit diagrams of (a) AND, (b) OR, (c) NOT, (d) NOR and (f) XOR operations.

| AND | | |
|---|---|---|
| Input $A$ | Input $B$ | Output |
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

| OR | | |
|---|---|---|
| Input $A$ | Input $B$ | Output |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

| NOT | |
|---|---|
| $A$ | $\bar{A}$ |
| 0 | 1 |
| 1 | 0 |

| NAND | | |
|---|---|---|
| Input $A$ | Input $B$ | Output |
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

| NOR | | |
|---|---|---|
| Input $A$ | Input $B$ | Output |
| 0 | 0 | 1 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 0 |

| XOR | | |
|---|---|---|
| Input $A$ | Input $B$ | Output |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

Figure 3.19
The truth table of AND, OR, NOT, NAND, NOR and XOR operations.

The elementary operations in mathematical morphology are *dilation* and *erosion*, which can be combined in sequence to produce other operations, such as *opening* and *closing*.

***Binary dilation*** combines 2 sets using vector addition of set elements. $A$ and $B$ denote 2 sets in $E^N$ with elements $a$ and $b$, respectively, where $a=\left(a^1,a^2,\ldots,a^N\right)$ and $b=\left(b^1,b^2,\ldots,b^N\right)$ being $N$-tuples of element coordinates. The binary dilation of $A$ by $B$ is the set of all possible vector sums of pairs of elements, one coming from $A$ and the other from $B$. Since $A$ and $B$ are both binary, the morphological operation applied on the two sets is called binary morphology.

In dilation, the roles of sets $A$ and $B$ are symmetric. Dilation has a local interpretation: $A\oplus_b B$ is the locus of all centers c, such that the translation (B)c (by placing the origin of B at c) hits the set A. The dilation by a disk-structuring element corresponds to the isotropic expansion algorithm in image processing; dilation by a small square (3 × 3) is an eight-neighborhood operation easily implemented adjacently connected array architectures and is the one known by the names *fill expand* or *grow.*

***Erosion*** is the morphological dual to dilation. It combines two sets using vector subtraction of set elements. If $A$ and $B$ denote two sets in $E^N$ with elements $a$ and $b$, respectively, then the binary erosion of $A$ by $B$ is the set of all elements $x$, for which $x+b\in A$, for every $b\in B$. Given a Cartesian grid, the two commonly used structuring elements are the 4-connected (or cross-shaped) and 8-connected (or square-shaped) sets, $N_4$ and $N_8$.

In practical applications, dilation and erosion pairs are combined in sequence: either dilation of an image followed by erosion of the dilated result or vice versa. In either case, the result of iteratively applying dilations and erosions is an elimination of specific image details whose sizes are smaller than the structuring element without the global geometric distortion of unsuppressed features.

### *Opening and Closing*

Aperture generally smooths out the contours of regions, eliminates small discontinuities and fine accents. The closing also tends to make more homogenous the



contour sections but, to the opposite of the opening, generally fuses together the fine discontinuities of the small and long segments, eliminates small holes, and fills the gaps in the contour. Such filters can be used to suppress spatial features or discriminate against objects based on their size distribution.

The opening of an image $A$ by a structuring element $B$, denoted by $A\circ B$, is defined as

$$A\circ B=\left(A\ominus B\right)\oplus B \tag{21}$$

So, the *opening* of $A$ through $B$ is realized by sequentially following the *erosion* of $A$ through $B$, and dilation of the result through $B$. Similarly, the closure of a set through a structuring element B indicates how $A\bullet B$ is defined as

$$A\bullet B=\left(A\oplus B\right)\ominus B \tag{22}$$

Which asserts that the closure of $A$ through $B$ is the dilation of $A$ through $B$, followed by the erosion of the result through $B$.

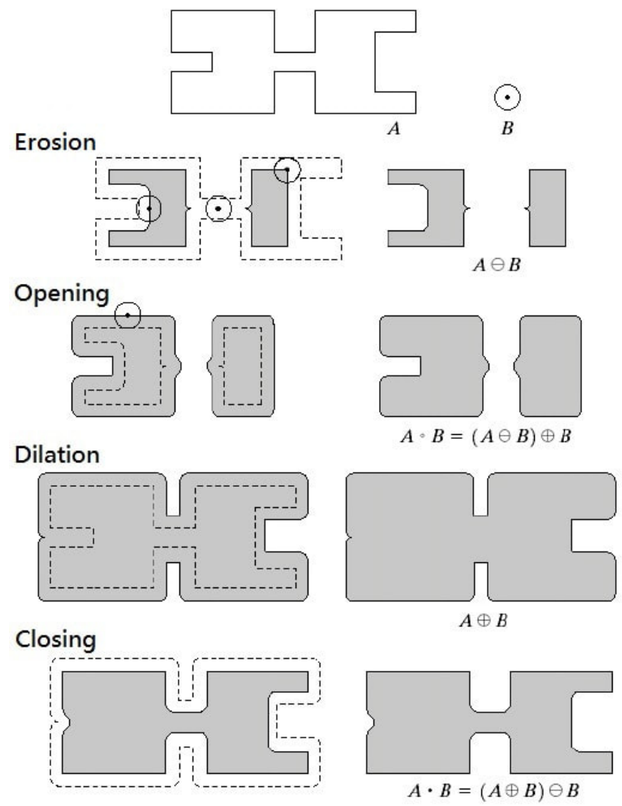



Figure 3.20
General diagram of morphological operations.

Source
Gonzalez, Rafael C., and Richard E. Woods. 2012. Digital Image Processing (2nd Edition). 2nd ed. ed. Marcia J. Horton. New Jersey: Prentice Hall.

## 3.2.4 Raster to vector conversion

Raster-to-vector conversion-also called image tracing, vectorization, or polygonization-is a key function in GIS systems and remote sensing image processing. There are two methods of conversion:

- line vectorization used in CAD to digitize raster images-often scanned from paper media such as maps or technical drawings. During this process, the user recognizes linear geometric elements and, after selecting the shape's appropriate tool, are converted and into vector format [124].
- Polygonal vectorization is used to extract features-or regions- from image classification results; this technique is also called *polygonization*.

In both methods, we move from raster representation to vector graphics representation.

The raster representation is formed by cells of a grid containing elements encoded with a numerical value, each element has a specific classification and each grid cell contains a classification value. The simplest classification system is binary, where 1 is identified as an entity's position, and 0 indicates the background.

***In the vector representation,*** the entities are geometric primitives called vector quantities; these are arranged in a *vector space*-also called linear space- defined as an algebraic structure composed of a *field*-the elements of which are called scalars-; *a set*-the elements of which are called *vectors*-; and *two binary operations*-called sum and multiplication- characterized by specific properties. The most commonly used vector spaces use the real field $\mathbb{R}$ and the complex field $\mathbb{C}$; called "real vector spaces" and "complex vector spaces". A real vector space is represented by $n$-ple of real $\mathbb{V}_n(\mathbb{R}) = \mathbb{R}^n$, in these cases a vector entity is represented by components

$$v = \begin{bmatrix} v^1 \\ v^2 \\ \vdots \\ v^n \end{bmatrix}, \; v \in \mathbb{R}^n \; , v_i \in \mathbb{R} \tag{23}$$

In this sense, a vector is defined as a particular matrix formed only of a column, or only of a row, therefore of dimension $n \times 1$. In the vector field, the geometric



primitives point, line, and area (or polygon) allow to produce a mathematical representation of the real object ( even if approximated ) that allows mathematical operators to study the properties of objects their interrelationships. Depending on the grade of approximation of these models, the results obtained will be more or less similar to reality. The starting raster image's high spatial resolution helps to keep the approximation margin minimal in the conversion.

The vector entities to be defined need a direction and a direction and are characterized by editable attributes. In addition, the vectors are independent of the resolution: they can be freely transformed (scaled, rotated, etc.) without any loss of detail and respect the topological characteristics of adjacency between regions.

The process of raster-to-vector conversion can be broken down into three basic operations.

- The first is skeletonization or line thinning, the process of reducing lines to a unit thickness at a specified resolution. The ultimate goal is to represent each pixel in a 0-1 binary matrix.
- The second operation is line extraction called vectorization, the process of identifying a particular set of data entities or coordinates that constitute a single line segment as represented on the input document.
- The third operation is topology reconstruction- the process of determining the adjacency relationships between all the lines.

In this paper [125], a comprehensive survey of skeletonization algorithms and their applications is provided; in particular, the following are discussed and summarized: different skeletonization approaches; topology preservation and parallel skeletonization; multi-scale skeletonization; applications and skeletonization performance evaluation.

This paper [126] reviews the methods and algorithms developed to date for document image vectorization; these algorithms are classified into six categories: *Hough transform-based, thinning-based, contour-based, run-graph-based, mesh-pattern-based; and sparse-pixel-based.*

The following describes the characteristics of the geometric primitives and the method of conversion from raster to vector.

***Point:***

The simplest primitive is the point and consists of an identification number and a position marked by a pair of coordinates $(x, y)$. The attributes associated with the point entity are assumed to be concentrated in an infinitesimal space. The union of two points represents a segment.

Raster to vector conversion:

A pixel in the raster model corresponds to a point in the vector model. Vector points coincide with the center of the pixel with which it is associated and are called *vertices*.

***Line:***

a line - also called a broken line - is a set of segments connected to each other and is recorded as an orderly set of points in the Cartesian plane. The attributes associated with a linear object maintain their value throughout the entire line extension.

Raster to vector conversion:

A line represented in the raster world consists of a series of adjacent and connected pixels that form a path. The way to transform this information in the vector world is to connect with small segments, the centers of the pixels formed a path, respecting the sequence (Fig.3.21). The line that forms the boundary of an entity is usually formed by direct strokes connected to curved strokes, with different curvature radius. The number and intensity of points to be acquired to vectorize a curve will be greater the smaller the radius of curvature. The result will be a set of connected segments whose position can be horizontal vertical, or oblique 45° and whose direction can be represented by four directions, called as the Rook move in the game of chess or eight directions called as the Queen move, as shown in figure 3.22 (a) and (b).

A vector line traces all pixels, forming vertices in every single cell of the array, even if there are pixels in the intermediate sections that join different directions. These pixels do not carry information but describe a " stepping" that is part of the representation's error margin and does not contribute to the data's geometry. This artifact has been optimized with an algorithm that reduces the number of $x, y$ coordinates required to define a line [127],[128]. The representation of curves by segments makes the data structure very simple, so operations concerning the geometry of the data are faster and more efficient than with raster data. Some software allows improving curved areas' visual appearance through a recursive algorithm for rational evaluation of Bézier curves[129].



***Area:***

the Area primitive describes a part of the plane within a closed line (Fig.2.23). Almost all features and regions of interest present on the artifact surface can be defined as areas. In the description of an area, the first point of the sequence of segments forming the boundary must coincide with the last point, thus forcing the figure's closure.

In GIS software, a sequence of points represents a line or a closed area depending on the layer's properties in which it is recorded. it can be defined that a polygon is composed of a group of lines and an area is composed of a closed polygon.

Raster to vector conversion:

The algorithm's speed is inversely proportional to the raster image's spatial resolution; images with an extensive dynamic range and high spatial resolution result in high computation times. Since spatial resolution is an essential feature to minimize approximation, the best approach is to work on dynamic range reduction by performing a pre-processing step and applying raster-to-vector conversion only to images with low dynamic range. This is the case for binary images in which there is no ambiguity between region edges. The vector conversion of areas in binary images is effective and fast: a set of pixels having the same value V and constituting a connected set is transformed into an area having as edges the sides included between the pixels having value V and those having value different from V (Fig.3.23). Identifying the edges of pixels that satisfy the condition mentioned forms a set of closed segments that correspond to a polygon.

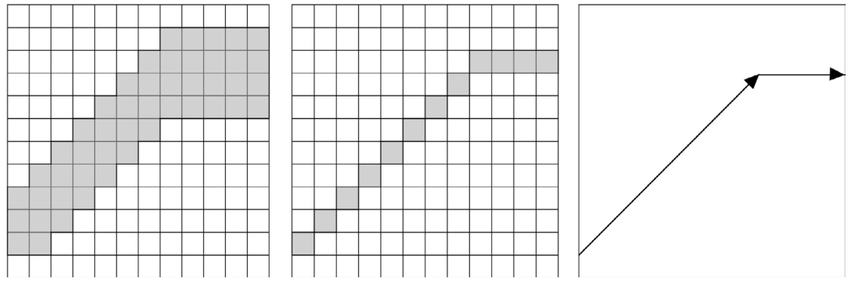



Figure 3.21
A simple Vectorization Algorithm.

**a** Original Image
**b** Thin ring whit chain coding
**c** Vector Data

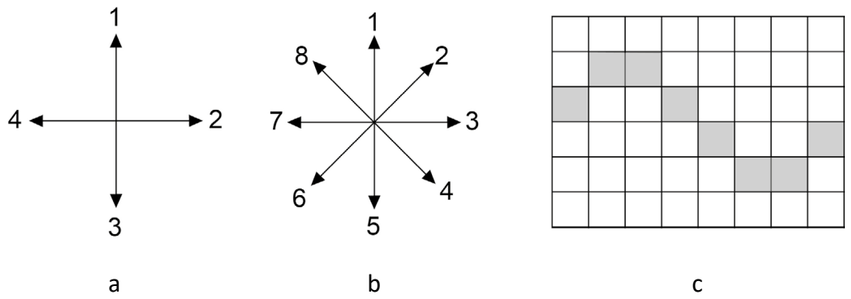



Figure 3.22
Flow Direction

**a** Four Directions (Rook's move)
**b** Eight Direction (Queen's move)
**c** Flow Directions in Queen's move (2,3,4,4,4,3,2)

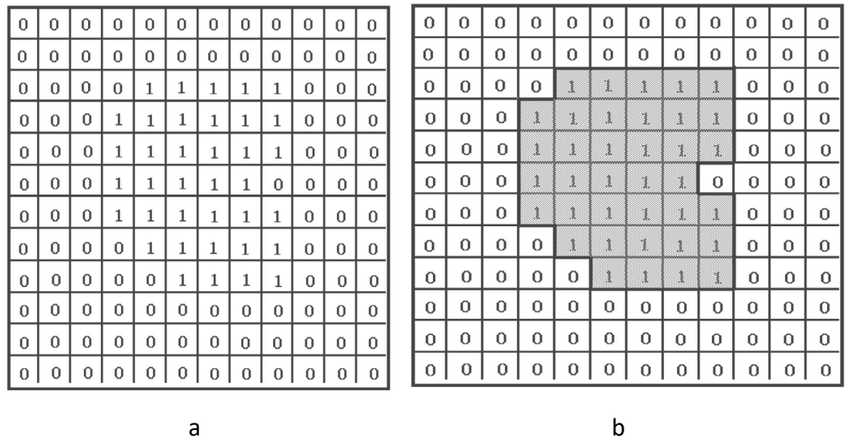



Figure 3.23
**a** Representation of an area in the raster model

**b** Construction of a vector area on the basis of the raster model

Section 3.3

# Choice of the software in which to implement methodology

This section describes the software on which various tests have been carried out, relating to the main analysis operations considered useful for our research purposes, such as automatic and semi-automatic extraction of raster images' features, binary masks extractions, morphologic operations, statistic elaborations on polygons, and data exportation operations in printing layouts for the creation of thematic maps.

## 3.3.1 Use of Matlab

MATLAB (short for Matrix Laboratory) is an environment for numerical calculation and statistical analysis written in C, which also includes the homonymous programming language created by MathWorks. It can be used to manipulate matrices, display functions and data, implement algorithms, and create user interfaces. It specializes in numerical calculation and is widely used to support a vast variety of applied fields of study. It can also be used on various operating systems, including Windows, Mac OS, GNU/Linux and Unix. Finally, exported files can be read by all other image processing software. Like AutoCAD, also MATLAB needs a license to be used; however, it contains several useful applications for the purposes of the proposed research. This section describes two Toolbox with a very simple user interface, which allow to carry out highly complex segmentation processes, without ever using the script code scripture window; this feature allowed even less expert users to gain excellent results in the methodology test process. In particular, some tools present in the Image Processing and Computer Vision Toolbox and in the Machine Learning and Deep Learning Toolbox appeared useful for the proposed research.

### 3.3.1.1 Image processing and computer vision Toolbox

Image Processing and computer vision Toolbox™ is a user-friendly interface, including a complete set of apps dedicated to image processing. A crucial characteristic for the researched methodology is the possibility of supporting high resolution 2D image elaboration; beyond this essential aspect, the toolbox includes all necessary operations for segmentation, on top of geometric transformations and the possibility of registering images between each other, using deep learning. All apps allow an iterative segmentation and mask improvement process, different methods can be tried, even in sequence, until the desired results are reached. Regions of interest (ROI) manipulation is done through morphologic operations, with edge detection and cleaning, and the binary mask creation is automatized and consequent to the segmentation done.

In particular, le most fruitful apps for our methodologic approach have been the Image Segmenter, which allows to carry out simple segmentations, Color Thresholder, allowing much more complex color segmentations and the Image Region Analyzer which allows to carry out an advanced alphanumeric analysis on the extracted binary masks. Following is a detailed description of these apps, with examples of application on cultural heritage images.

#### Image Segmenter App

Allows image segmentation with an iterative approach through a trial and repetition process until the desired result is reached.

This app includes three segmentation tools, only one of which is completely automatic, while the other two allow operators to select main figure and background by hand. The app allows three kinds of operations: 1. Segmentation and consequent binary mask creation; 2. To add or eliminate regions from the obtained mask; 3. Finish the mask through various operations, such as edge cleaning and morphological operations. In addition, the app displays steps taken while creating the segmentation in the History panel of the Data Browser.

This app has given excellent results on diagnostic X-ray images and photographs in visible light in which the object and the background are clearly distinct. Below are described in detail only those app tools useful for our research purposes.

***1. Segmentation tools with binary mask extraction:***

***Threshold:*** an automatic technique where you specify an intensity value that you want to isolate. This technique can be useful if the objects you want to segment in the image have similar pixel intensity values and these values are easily distinguished from other areas of the image, such as the background. This tool allows using a manual or adaptive threshold. Each option allows the user to operate iterative controls to optimize the threshold. For example, with manual threshold, it is possible to choose the threshold value using the slider. With adaptive threshold, it is possible to choose the sensitivity using the slider.

***Auto Cluster*** is a fully automatic tool, grouping image characteristics in a binary segmentation without image initialization, but using the Statistics and Automatic Learning Toolbox. This tool is based on Lloyd's k-means algorithm, in the well-known k-means formulation a whole k and a set of n data point in. $\mathbb{R}d$ The goal is to choose k centers to minimize $\phi$, the sum of the square distances between each point and its neighboring center [130]. In order to quantify visual differences, the Auto Cluster converts the image into L*a*b* color space (also known as CIELAB or CIE L*a*b*, derived from the CIE XYZ trichrome values) which consists of a brightness level 'L*', a color level 'a*' indicating where the color is located along the red-green axis, and a color level 'b*' indicating where the color is located along the blue-yellow axis. All color information is in the 'a*' and 'b*' layers, so it is possible to measure the difference between two colors using Euclidean distance metric. The tool classifies colors in space 'a*b*' using k-means clustering, processing each object in the image as having a position in space and creating partitions so that objects within each group are as near as possible and as distant as possible from objects in other groups. Since color information exists in the 'a*b*' color space, our objects are pixels with 'a*' and 'b*' values; thus the tool classifies objects into two groups.



***Graph cut*** is a semi-automatic segmentation technique to separate elements between the foreground and the background. Instead of tracing the boundary, the system allows operators to use lines and curves to specify the extent of the object of interest. The interface does not require operator input to be very precise, element identification is done by drawing lines or shapes on the image. The drawing is done in two moments: first identifying what is required in the foreground and then what is required in the background. The tool automatically segregates the image according to traced lines, even if the lines are distant from the object boundary. Also, in this app the approach is iterative, it is possible to refine the segmentation by tracing more lines on the image until the result is satisfying. Automatic segmentation applies the graph theory to obtain quick segmentation [131]. The algorithm creates a graph of the image where each pixel is a node connected by weighted edges. The higher the probability that pixels are related the higher the weight. The algorithm cuts along weak edges, achieving the segmentation of objects in the image.

When filling out the Information Model this tool can be useful in case the features to be extracted within the object present step edges and are characterized by similar pixel intensity values, easily distinguishable from other image areas, for example it could be useful to extract a mask of lacunae filled with white stucco. In general, the result is strongly influenced by the kind of background, and the best results are obtained with a non-texturized uniform background. An example of use for this purpose is shown in chapter 5, in the Madonna with Child case study of section 5.3, in which auto Cluster was used to segment some areas of a canvas using a visible light image.

When filling out the Object Model, this tool can be useful to eliminate the background from visible light images taken to document artifacts' existing conditions before and after restoration. In fact, binary mask extraction can be used to obtain the object's silhouette, thus the object's outlines, which at present are hand drawn by operators in thematic maps.

When using the Auto Cluster and Graph Cut segmentation tools it is possible to include texture information as an additional evaluable element for segmentation, in this case, applications use Gabor filters to filter the image texture as a pre-processing step in segmentation. Gabor filters are simple cells present in mammals

vision system, considered useful to distinguish textures by humans. For this reason they are used in the design of algorithms to recognize textures [132][133]. The inclusion of texture obviously requires a greater usage of the device's graphics card, especially in case of high spatial resolution images, and it doesn't always guarantee best results.

***2. Tools to add or delete regions from the obtained mask:***

To add or delete regions to the created mask, it is possible to use the tools in the Add to Mask menu. In case of silhouette extraction, (i.e. object modeling) these enhancement functions are very useful in artifacts having light reflections, such as statues or bronze, gold or glass frames, and can also be used to improve feature recognition.

***Local Graph Cut (grab cut)***

A semi-automatic technique, like the Graph Cut method, that allows to refine segmentation by drawing additional lines on the image to identify regions of interest (ROI).

***Flood Fill***

It is an automatic technique, only the points to be selected must be specified and the tool segments areas with similar intensity values. A very useful function is the adjustment of tolerance metric distance, where the Euclidean flood fill can be used based on the connected Euclidean distance from the selected point, or the Geodesic flood fill based on the geodetic distance from the selected point[1][134]. Also, in this tool it is possible to set texture filtering for better area recognition.

***Draw ROI***

A manual technique for drawing closed shapes to delineate the region to be segmented. It is possible to draw rectangles, ellipses, polygons or freehand shapes.

1 In the mathematical field of graph theory, the distance between two vertices in a graph is the number of edges in a shortest path (also called a graph geodesic) connecting them. This is also known as the geodesic distance. Notice that there may be more than one shortest path between two vertices. If there is no path connecting the two vertices, i.e., if they belong to different connected components, then conventionally the distance is defined as infinite.



***3. Tools for binary mask refining:***

Image Segmenter provides several tools that can be used to optimize and correct small imperfections in the created mask. Again, only tools appropriate for research purposes are listed.

***Morphological operations***

This tool has the morphological techniques of expansion, erosion, opening and closing of the mask described in section 3.2.3.

***Clear borders***

A fast and fully automatic way to remove small regions on the edge of the image.***Fill holes***

A quick way to fill small gaps in foreground regions.

***Invert mask***

Sometimes segmentation can be easier to evaluate if the foreground and background are inverted, this option can be used and switched throughout the segmentation process.

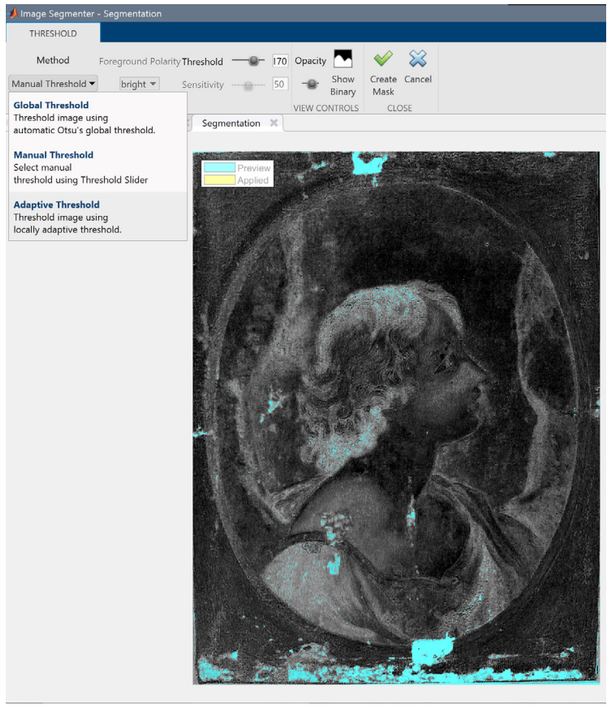



Figure 3.24
Matlab screenshot, Image Segmenter app. Windows of Treshold Metod. Example of segmentation using Threshold manual tool.

Figure 3.25
Matlab screenshot, Image Segmenter app. Windows of Morphology operation.

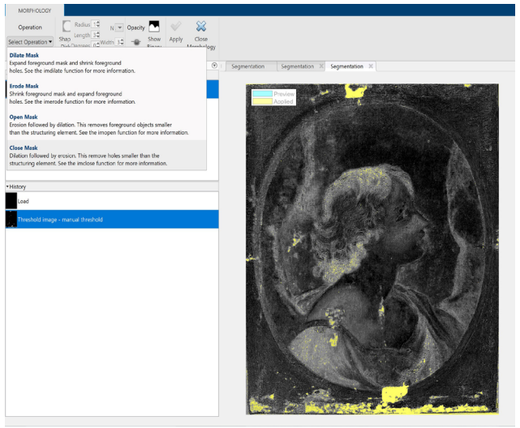
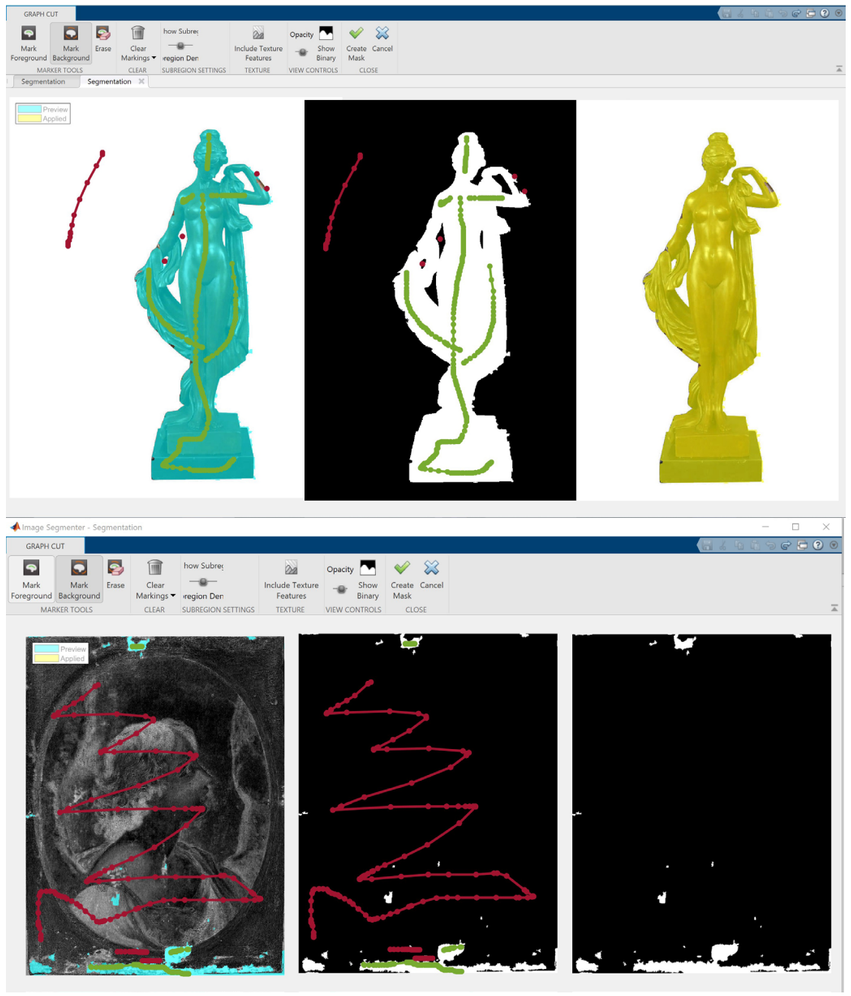
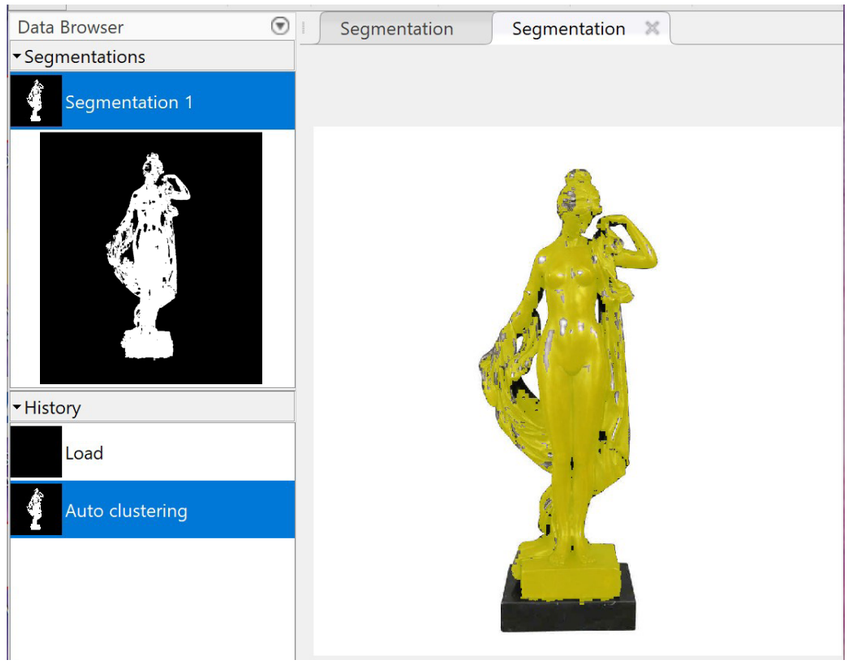


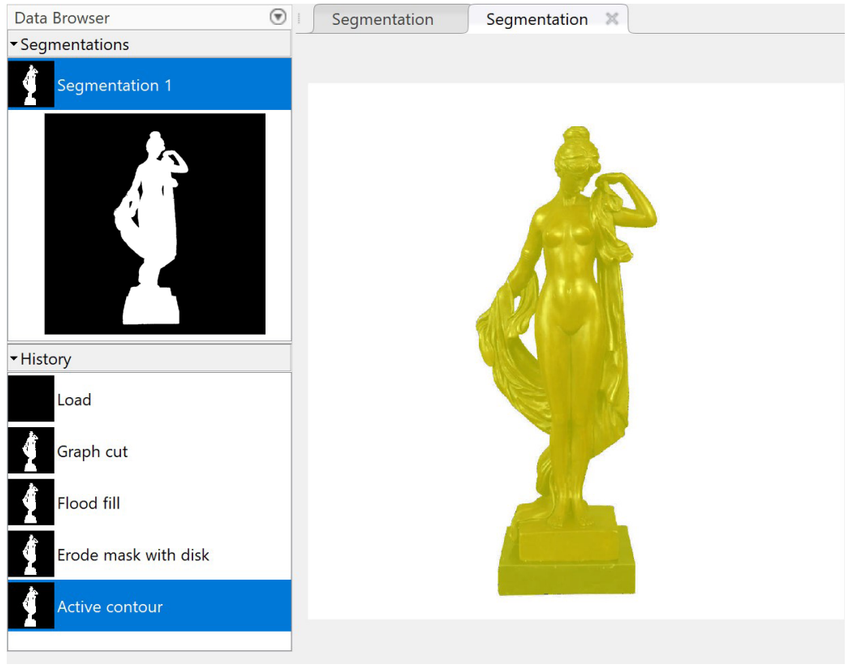
Figure 3.26
Matlab screenshot, Image Segmenter app. Example of segmentation using only the Graph cut tool. The more scribbles done, more the accuracy of the Graph Cut increases.








(a)




(b)

Figure 3.27
Matlab screenshot.
Image Segmenter app.

(a)Example of segmentation using only the Auto Cluster tool.
The Auto cluster has problems with light reflections on the object.Also, the base of the statue is a different color and the auto cluster considers only two color groups: the background and the color of the statue.

(b) Example of segmentation using a series of tool.
1-Graph Cut: to global segmentation
2- Flood fill: to close holes in the binary mask caused by light reflections.
3-4 Erode Marsk and Active contur: morphological operation to delimit the silhouette of the statue precisely and eliminate unwanted pixels.

## Color Thresholder App

The Color Thresholder application allows to make complex segmentations of color images. It allows to work in four color spaces: RGB, HSV, YCbCr, L*a*b*. This property is very appropriate to the purpose of this research as each color space shows characteristics according to different criteria, making certain calculations more convenient or providing a more intuitive way to identify colors. Thus, certain features could be more easily segmented into one space than another. The app shows the images in three types of representations: photo mode, 3D color space plot and histogram for each channel. The four representations of the image are shown at the same time in a single working window and it is possible to segment into several representations at the same time (Fig.3.28). All the operations performed are shown in real time in the photo representation model.

- In the Photo Representation mode, the result of each operation is displayed. It is possible to perform an automatic segmentation initially by selecting a region of interest. The binary mask can be modified using the other representation modes.
- In the 3D color space plot, pixel values correspond to specific points in the three-dimensional space and a polygon can be drawn to contain values corresponding to the desired characteristics. This segmentation mode is not very practical.
- In histogram mode for each channel the color components are defined by histogram curves. It is possible to switch in the dynamic range of each channel with a slider that sets the threshold. This method is very practical and functional; the result shown in real time accelerates segmentation process.

The mentioned apps include automatic extraction in binary masks of the segmentation results, once the desired segmentation is obtained it is possible to export in the Matlab workspace the final mask image and also the segmented version of the original image. Moreover, it is possible to automatically generate a script code corresponding to the operations performed and use it to apply the same steps to similar images, providing reproducibility of the results. Saving the code requires the Statistics and Machine Learning Toolbox.



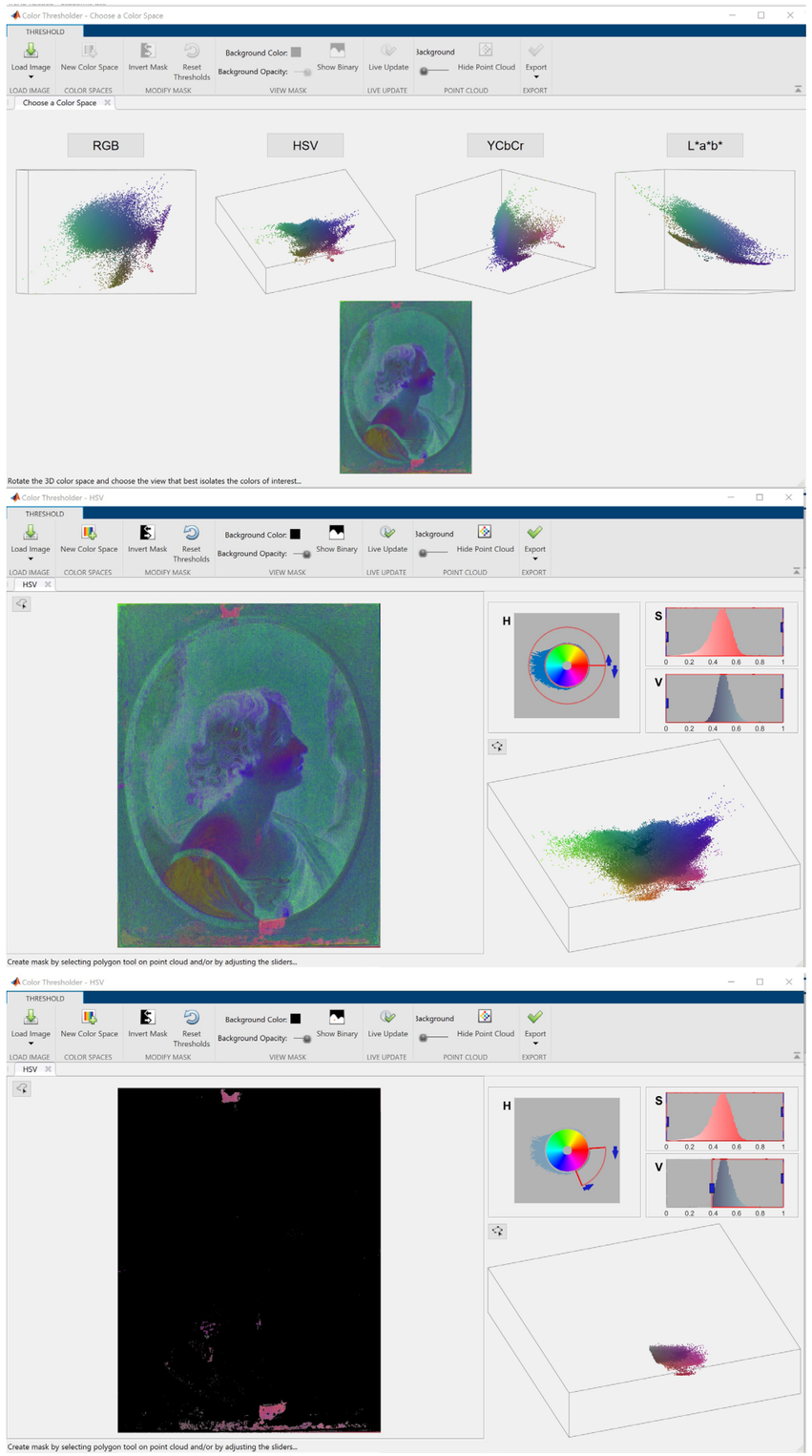



Figure 3.28
Matlab screenshot, Color Thresholder app
Example of segmentation on a pseudocolor image using the HSV model.

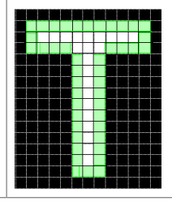
## Image Region Analyzer App

This application can be used only on binary or ternary masks and allows to measure a set of properties for each region. The properties are displayed in a table where each row is an identified region and each column is a property of the region, such as the area, perimeter, and orientation. Region properties can be filtered and queried with Boolean operators. The filtered regions can be exported into a new binary mask in the Matlab workspace. Therefore, this application allows to categorize characteristics by exporting one mask for each searched group or characteristic. The following table shows properties useful for image analysis of historical or artistic interest objects.

Table 3.2
Properties of Image Region Analyzer app useful for image analysis of historical or artistic interest objects.

| PROPERTY NAM | DESCRIPTION | PRACTICAL USE FOR ARTIFACTS |
|---|---|---|
| 'Area' | Actual number of pixels in the region, returned as a scalar. | This property is very useful as it allows to highlight the most extended and relevant degraded areas on the artifact's surface. It can be used to calculate the quantity of material to be used for intervention. |
| 'Euler Number' | Number of objects in the region minus the number of holes in those objects, returned as a scalar. | This property is useful to highlight in which of the extracted areas there is a higher presence of voids (or areas) corresponding to objects external to the region of interest. This parameter can be used for a more precise calculation of the region of interest's area. |
| 'Extent' | Ratio of pixels present in each extracted region to pixels in the total boundary box, returned as a scalar. | This property is useful as it makes immediately evident which region occupies more space in percentage as compared to the entire surface of the researched artifact. |
| 'Filled Area' | Number of pixels present in the selected region, returned as a scalar. | The number of pixels is useful to make calculations on spacial resolution and on details. |
| 'Major Axis Length' | Length (in pixels) of the major axis of the ellipse that has the same normalized second central moments as the region, returned as a scalar. | This property can be useful to identify a mosaic's execution technique by studying each indiviual tile. |
| 'Minor Axis Length' | Length (in pixels) of the minor axis of the ellipse that has the same normalized second central moments as the region, returned as a scalar. | This property can be useful to identify a mosaic's execution technique by studying each indiviual tile. |



| | | |
|---|---|---|
| 'Orientation' | Angle between the x-axis and the major axis of the ellipse that has the same second-moments as the region, returned as a scalar. The value is in degrees, ranging from -90 degrees to 90 degrees.<br><br>This figure illustrates the axes and orientation of the ellipse. The left side of the figure shows an image region and its corresponding ellipse. The right side shows the same ellipse with the solid blue lines representing the axes. The red dots are the foci. The orientation is the angle between the horizontal dotted line and the major axis.<br>  | This property can be useful to identify a mosaic's execution technique by studying each individual tile or to study paintstrokes' orientation on a surface. |
| 'Perimeter' | Distance around the boundary of the region returned as a scalar.<br><br>The perimeter calculates the distance between each couple of adjacent pixels around the edge of the region. So this parameter calculates only the pixels contiguous to the region. This figure shows the pixels included in the perimeter calculation for this object.<br>  | This property can be used in all areas of cultural heritage with ever changing purposes. |

### 3.3.1.2 Machine Learning and Deep Learning Toolbox

Statistics and Machine Learning Toolbox™ offers graphical interfaces that allow the user to operate functions to describe, analyze, and model data. Regression and classification algorithms provide to draw inferences from data and build predictive models either interactively or programmatically.

For multidimensional data analysis and feature extraction, the toolbox provides principal component analysis (PCA) methods and supervised, semi-supervised and unsupervised machine learning algorithms, including Self-Organizing Maps (SOM). Compared to the image processing toolbox, some of these applications require extensive knowledge of Matlab functions and digital image attributes; for these reasons, they cannot be used by an inexperienced user and need special training.

***Neural Net Clustering SOM***

The Neural Net Clustering application uses Self-Organizing Maps (SOM) to perform feature classification through clustering, a neural network application that involves clustering data by similarity and spatial placement, respecting the topological distance of features. In the clustering process, the parameters can be chosen by the operator, input images can be selected, the network can be trained, and the results can be analyzed using various visualization tools. It's possible to evaluate the performance of the network on a test set. If satisfied with the results, the network can be requalified with re-settings or more extensive data sets. It is possible to generate the script function automatically to reproduce the results or customize the training process. It is also possible to save the trained network to test it on new data or use it to solve similar clustering problems. The app also provides the ability to generate various deployable versions of the trained network [135][136].

***Principal Component Analysis (PCA) and Independent Component Analysis (ICA)***

As discussed in Section 3.2.1, PCA is a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables, called principal components (PCs). The first PC output represents the



highest variability in the data, and subsequent components have less variability than the previous one. In ICA, multi-dimensional data is decomposed into components that are maximally independent in an appropriate sense. ICA differs from PCA in that the low-dimensional signals do not necessarily correspond to the directions of maximum variance; rather, the ICA components have maximal statistical independence. In practice, ICA can often uncover disjoint underlying trends in multi-dimensional data.

PCA and ICA in Matlab is used for several aims[2], i.e., packages and codes were created to analyze inductive thermal models for the detection of defects present in certain materials [137]a single-channel blind source separation is proposed to process the ECPT image sequences.

This package could be used to study the thermographic survey of historical buildings.

To help the non-expert user, a new easy-to-use graphical user interface (GUI) for applying PCA to images was recently created in Matlab [138]. The GUI allows you to load any type of image and choose the number of outputs to generate.

As for FastICA, there is a free (GPL) package for MATLAB that implements the fast-fixed-point algorithm for independent component analysis and projection pursuit. It features an easy-to-use graphical user interface and a computationally powerful algorithm. The free package for Matlab can be downloaded at this link[3].

2 https://it.mathworks.com/matlabcentral/fileexchange/?category%5B%5D=211&q=PCA

3 http://research.ics.aalto.fi/ica/fastica/

## 3.3.2 The use of QGIS

QGIS is an Open Source Geographic Information System born in May 2002 and is a free software available to anyone possessing a personal computer; currently it can be used on most Unix, Windows and OS X platforms. It is developed using Qt software tools (https://www.qt.io) and the C++ language, with a slim and user-friendly user interface (GUI). It is an easy-to-use GIS that offers numerous features for visualization, acquisition, advanced analysis and presentation of data in the form of sophisticated maps, atlases and reports. QGIS supports a wide range of raster and vector data formats, and several formats can be added using plugins. QGIS is released under the General Public License (GPL), which allows to inspect the source code ensuring the user full accessibility and software modification.
The numerous studies on quantitative description of the Earth's surface topographic characteristics with GIS systems have defined a series of parameters and methodologies, useful to the objective description of the features of any object represented in a raster image; whether from satellite or not. For this reason, it was easy to try and integrate the phases of proposed methodology in QGIS. In particular, we have chosen to definitely use free and open source QGIS software as it offers a series of indispensable advantages for the development of applications useful for documentation.
Following is a short list of six general types of functionalities useful for the documentation for restoration and conservation of cultural heritage.

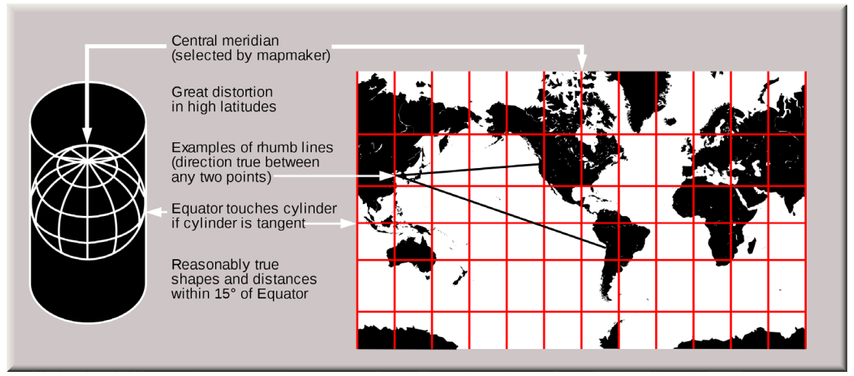



Figure 3.29
Modified centrographic cylindrical projection of Mercator.



***Viewing data***

2D or 3D vector and raster data can be displayed in different formats and projections without converting them into an internal QGIS format. Supported formats also include Tables, different types of Raster like jpeg, png, tiff., vectors extracted from other software like CAD, ARCGIS, and Adobe Illustrator and Spreadsheets (ODS / XLSX).

***Explore data and compose maps***

Spatial data can be processed with a very easy to use graphical interface that has many practical tools including: Reports, General View Panels, Spatial Bookmarks, Text Notes, Identification/Selection Functions, Edit/Display/Search Attributes, User Defined Data Labeling, User Defined Symbology for Vectors and Raster, Advanced Print Layout with measurement scale bar and copyright label and logos for thematic mapping.

***Data creation, editing, management and export***

Data can be created and exported in many formats. QGIS offers vector creation and digitizing tools (including raster to vector conversion), geo referencing plug-in for geo encoding images, spatial database management and creation of spatial database tables, tools to manage vector attribute tables, saving screenshots as geo referenced images, DXF-Export tool with advanced export capabilities and CAD drawing functions.

***Data analysis***

QGIS currently offers tools for vector analysis, raster analysis, sampling, geo-processing, geometry and database management. The data can be analyzed using integrated GRASS tools, which include the full functionality of over 400 modules. In addition, it is possible to work with the Processing plug-in that provides an analysis framework for querying native and third-party algorithms from QGIS. All analysis functions are performed in the background, allowing users to continue working on the project while the algorithm is being processed.

***Exporting projects with Web GIS***

Possibility of sharing the methodology by promoting the consistency of adopted solutions and obtaining feedback from third parties.

***Extension of functionality through plug-ins***

QGIS can be adapted to different research purposes due to the extensible plug-in architecture and libraries that can be used for plug-in creation.

***Python Console***

new applications can be implemented with C++ or Python scripts. For scripting, a Python console is integrated.

In particular, the last two features listed allow the development of the entire methodology in a single software by implementing in QGIS all the algorithms required to adapt the software to the needs of the proposed research.

### 3.3.2.1 Association to geo-referred spatial coordinates through world file.

A GIS database is characterized by association of records to spatial coordinates; each inserted file must necessarily keep to specific and real measures precise in relation to reference systems based on cartographic projections.

Cartographic projections represent terrestrial surface or a portion of it on a plane, transforming the Earth's spherical shape (3D) into a flat form (2D) so as that representations can be made on flat layers. Reference systems (SR) define, through coordinates, how maps are connected to real positions on the Earth. Cartographers have developed various cartographic projection techniques to accurately represent the Earth's spherical surface in two dimensions (Fig.3.29).

Choice of the type of projection and reference system to be used depends on the object's extension and needed analysis, in our case the best projection to be used for a certain object depends on its size and on documentation purposes. For example, a projection may present unacceptable distortions if used for objects of vast dimension (as in the case of Land Art) but could be an excellent choice for a small object. The properties of a cartographic projection may influence some design characteristic of the map. This requisite does not represent a limitation per



for small objects and can be used to the methodology's advantage. In fact, users are obliged to a rigid control on the size of inserted images, which must be in 1:1 scale.

In addition, it may be useful to establish points within the image to be used as markers. Distance between markers should be the same in the raster image as in the real object.

This procedure obliges to respect spatial consistency image points and object points, thus obtaining truthful analysis, with a minimal error percentage.

The reference system we used is based on a modified cylindric *centre-graphic* projection by Mercator, also called *Mercator's Projection.* This projection keeps the distance scale constant in all directions around each point, maintaining angles and shapes of small objects, making it appropriate to our needs (Fig.3.29).

In QGIS the Mercator Projection corresponds to two metric reference systems such as WGS 84 Pseudo-Mercator / EPSG 3857 or EPSG 6871.

The most accurate procedure for the insertion of artefacts' images, both small and large, can be performed using the world file technique, a collateral file to the image of six lines of plain text, used by geographic information systems (GIS) to geo-reference images of raster maps. The file specification was introduced by Esri[4], and is composed of six coefficients of an affine transformation that describes the position, scale and rotation of an image on a map. The raster images are memorized as data in which each cell of the image has a row and column number, the world file sets a transformation called *image-to-world* that converts the image coordinates into real world coordinates. World files can be created with any editor and must be stored in the same folder as the image. The world file uses the same name as the image, with the letter *w* appended, sometimes the naming convention varies using the first and third characters of the image file's suffix and a final letter '*w*' as the world file suffix (table). For images that lack an extension or have an extension that is shorter than three characters, the letter *w* is added to the end of the file name without altering it.

4 https://desktop.arcgis.com/en/arcmap/10.3/manage-data/raster-and-images/world-files-for-raster-datasets.htm

Table 3.3
Example of world file extension types.

| RASTER DATA FILE | WORLD FILES |
|---|---|
| image.tif | image.tfw, or image.tifw |
| image.bil | image.blw or image.bilw |
| image.jpg | image.jgw or image.jpgw |
| image.raster | image.rasterw |
| image.bt | image.btw |
| image | imagew |

The *image-to-world* transformation is an *affine transformation* of six parameters. The generic meaning of the six parameters is expressed as follows:

$$x1 = Ax + By + C$$
$$y = Dx + Ey + F \quad (24)$$

Where

$x1 =$ calculated $x$-coordinate of the pixel on the map

$y1 =$ calculated $y$ - coordinate of the pixel on the map

$x =$ column number of a pixel in the image

$y =$ row number of a pixel in the image

$A = x$ – scale; dimension of a pixel in map units in x direction

$B, D =$ rotation terms

$C, F =$ translation terms; $x, y$ map coordinates of the center of the upper left pixel

$E =$ negative of $y$ – scale; dimension of a pixel in map units in y direction

The $y$ (E) scale is negative because the origins of an image and a geographic coordinate system are different. The origin of an image is in the upper left corner, while the origin of the map coordinate system is in the lower left corner. Values of the rows in the image increase from the origin to the downside, while the values of the y coordinates in the map increase from the origin to the upside. Transformation parameters are stored in the *world file* in the order shown in Table. 3.4.



| WORLD FILE APPEARANCE | MATCHING PARAMETERS | |
|---|---|---|
| 0,0169323213156 | **A** | x-scale; dimension of a pixel in map units in x direction |
| 0.00000000000000 | **D** | rotation terms |
| 0.00000000000000 | **B** | |
| -0,016931918656 | **E** | negative of y-scale; dimension of a pixel in map units in y direction |
| 0.00000000000000 | **C** | translation terms; x, y map coordinates of the center of the upper left pixel |
| 0,2677 | **F** | |

Table 3.4
World file appearance and parameter matching.

To facilitate the operator in writing the World file we use the following parameter descriptions:

- Line 1:A x-component of the pixel width (x-scale)- pixel size in east-west direction
- Line 2:D y-component of the pixel width (y-skew)- rotation terms about y-axis
- Line 3:B x-component of the pixel height (x-skew)- rotation terms about x-axis
- Line 4:E y-component of the pixel height (y-scale)- pixel size in north-south direction
- Line 5:C x-coordinate assume value 0
- Line 6:F y- coordinate image height negative value in meters.

To achieve numeric values corresponding to parameters **A** and **E** it's necessary to know the artifact's real dimensions and the raster image's size in pixels. In the raster image, values must have been assigned in 1:1 scale, i.e. file centimeters must correspond to real centimeters. Spatial resolution will have to be the same for all acquired images.

After performing these operations, the value of **A** $(x)$ can be obtained as follows

$$x = \frac{a}{b} \quad (25)$$

where $a$ corresponds to the width in cm and $b$ corresponds to the width in pixels. The value of **E** can therefore be obtained in the same way using height equivalents.

In the following table we give a practical example of a raster image with real values.

| | |
|---|---|
| **Width in cm** 26,77 | **Height in cm** 38,3 |
| **Width in pixel** 1581 pixel | **Height in pixel** 2262 |
| **A value**<br>0,0169323213156 | **E value**<br>-0,016931918656 |

These values result from the following proportion

$$a : b = d : c$$

$$a = \frac{b \cdot d}{c} = \frac{b}{c} \qquad (26)$$

$$z = \sqrt{\frac{b}{c}}$$

Where

$a$ corresponds to the value of $n$ $cm^2$ present in a $pixel^2$

$b$ corresponds to the value of the area in $cm^2$

$c$ corresponds to the value of the area in $pixel^2$

$d$ corresponds to the value of a $pixel^2$

$z$ corresponds to the magnitude value in meters of a pixel

**C** and **F** values correspond to the position of the object in relation to Greenwich meridian and the equator: by assigning **0** value to **C** the image will have the lower left corner positioned at their intersection. The value of **F** must correspond to the image height in meters, so that no negative values will be obtained during measurements and statistical evaluations.

**D** and **B** values, related to rotation, must always be equal to 0, except if it is necessary to rotate the image for documentation purposes.



### 3.3.2.2 Raster interpretation and analysis

GIS projects are almost always based on raster images, mainly using aerial or satellite photos, some types of Regional Technical Maps and often scans of papers or other historical documents; for this reason, many tools are dedicated to raster analysis and to features' extraction.

***Raster data Interpretation***

GIS considers a raster as a map in which each pixel is characterized by a position and a spatial dimension: as for the position, the central point of each pixel is characterized by a latitude and a longitude, expressed in meters or degrees depending on the reference system, while each pixel's dimension is a small square with a "real" size side, expressed in the real measuring unit used by the map's reference system. Furthermore, each pixel can have another property, which varies according to the type of raster; each pixel can be associated to a value which can represent different quantities. For example, in a DTM (Digital Terrain Model), each pixel is associated to sea level quota, in a temperature map, each point is associated to the corresponding degree value, etc.

Depending on their format, some raster maps have within them a coded system of coordinates, while others must be associated to a world file; as in the case of artifact images. There are many raster formats which can be used in a GIS setting. In general, for orthophotos, satellite images and topographic maps, we use tiff or geotiff formats (when the system of coordinates is already coded in the file).

For DTM digital terrain models, i.e. maps which contain quota information, thus allowing to work in three dimensions, various grid type formats (.dat, .xyz, .asc, grd, ecc.) are commonly used.

QGIS can register and analyze all formats currently used for photographic documentation, all raster formats read by QGIS can be seen at this link[5], in particular those used for the documentation of artifacts' restoration are the CAD AutoCAD DWG raster layer, the GIF Graphics Interchange Format, the JPEG JFIF File Format, the Geospatial PDF, the PNG Portable Network Graphics, Tiff and Geo Tiff.

5 https://gdal.org/drivers/raster/index.html

Each uploaded raster image includes information relating to the system of coordinates in which it was created or inserted, to the extension, its resolution (i.e. the size of its pixels), to the reported values (for example minimum and maximum quota), to the presence of void values. QGIS allows to access this information by a property panel associated to the raster.

***Value Distribution***

Two main types of raster can be found in a GIS setting: with discrete value or continuous value. In the first case, the raster values are few and they identify uniform data classes, a very common example of discrete value maps are those based on the presence or absence of a given element: for example, binary images in which pixels have a 1-0 value. Also, some parts of a raster map can have a void value, meaning that in those parts there is no pixel. In the case of continuous values, the raster is associated to conditions or phenomena which appear over all the territory, such as elevation, temperature, land incline, with no easily detectable limits, but with graded shadings between the areas. Example of a continuous value raster map is an aerial photo in which each pixel is associated to a value identifying color, another example is a DTM in which each pixel is associated to the quota value. Possible values for this kind of raster theoretically go from minus infinite to plus infinite, and it's very hard to identify areas with uniform features and well defined boundaries. This category also includes artifact images both in visible and multispectral light, in which even if the data is discrete it's hard to clearly identify homogenous areas. Respective analysis statistic elaborations, like the BSS algorithm outputs, help in classifying these areas.

***Analysis***

QGIS has various raster analysis functions, listed below are the ones appropriate to the proposed research.

***Raster Co-registration***

As mentioned, documentation cards for restoration projects are based on various images of the same subject, which must respect geometrical consistency and be



perfectly registered between each other. Geometric and morphologic consistency of individual images is respected thanks to image insertion with the world file system. Geo Referencer is a further Plugin for image insertion, word file and Geo. Tiff production. This tool allows to geo-reference a raster, identifying by hand some points on the raster itself and automatically assigning precise coordinates. The procedure includes selection of points and the choice of a type of pixel transformation. The Geo Referencer tool can be used to co-register one image to the other through the use of these marker-type control points; the more control points are used, the better the result. Based on transformation parameters and on the number of points used, the plugin calculates the parameters and registers images and the figures' internal morphology.

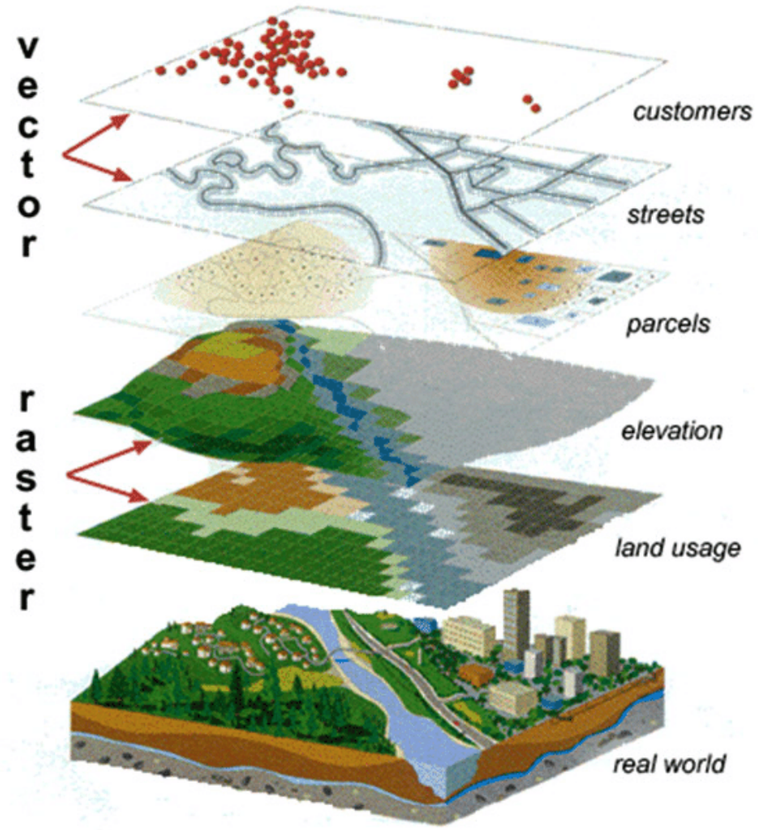



Figure 3.30
Graphic example of raster and vector file in GIS.

***Principal Component Analysis***

In QGIS the Principal Components Analysis (PCA) can be performed with two tools: the Semi-Automatic Classification Plugin and the GRASS i.pca algorithm in the Processing Tools list.

The Semi-Automatic Classification Plugin (SCP) is a free open source plugin for QGIS that allows for semi-automatic classification-supervised and unsupervised-of remote sensing images. The general goal is to provide a set of interconnected raster processing tools to create an automated workflow and facilitate the classification of land cover, however it can also be used for tasks other than remote sensing. The plugin features an input window for multi-band multispectral images and the PCA algorithm. The principal component transformation provides a new set of bands (principal components) having the following characteristic: principal components are uncorrelated; each component has variance less than the previous component. Given an image with N spectral bands, the principal components are obtained by matrix calculation.

where:

$$Y = D^t X \tag{27}$$

- *Y* = vector of principal components
- *D*= matrix of eigenvectors of the covariance matrix in $C_x$ X space
- *t* denotes vector transpose

And *X* is calculated as

where

$$X = P - M \tag{28}$$

- $P$ = vector of spectral values associated with each pixel
- $M$ = vector of the mean associated with each band

Thus, the mean of $X$ associated with each band is 0. $D$ is formed by the eigenvectors (of the covariance matrix $C_x$) ordered as the eigenvalues from maximum to minimum, in order to have the maximum variance in the first component. This way, the principal components are uncorrelated, and each component has variance less than the previous component, usually the first two components contain more than the 90% of the variance.

The plugin automatically arranges the output images on different layers within the project naming them with a progressive number. In addition, a report .txt is saved along with the PCA bands, containing the covariance matrix, correlation matrix, eigen vectors, and eigen values [139].



GRASS's i.pca tool uses the same analysis process and is based on the algorithm provided by Vali (1990), that processes $n\ (n>=2)$ input raster map layers and produces $n$ output raster map layers containing the principal components of the input data in decreasing order of variance ("contrast"). The output raster map layers are assigned names with .1, .2, ... .$n$ suffixes. The numbers used as suffix correspond to percent importance with .1 being the scores of the principal component with the highest importance 6.

To use both tools correctly, all images inserted in QGIS must be merged to form a single multi-band image. An example is shown in section 4.7.2.

The ICA algorithm is currently not present in QGIS but can be inserted through the processing script in Python.

***Binarization with the raster calculator***

In QGIS the quickest tool to classify pixel values and extract binary masks is the *Raster Calculator* tool, which allows to make calculations based on the pixel values present in the raster. Results are written in a new raster with a format supported by GDAL. To generate reclassification it's necessary to write specific expressions in the *raster calculator expression* window. The Binarization process can be carried out simply by choosing a threshold value to subdivide the pixel values for gray-scale images. The choice of threshold value may vary depending on the image, a first test can be done by calculating the average pixel value and choosing it as global threshold value. If the result is not in line with expectations, operators may use *Value Tool* manually to select a threshold value, analyzing the pixels in the borders of interested areas. By simply skimming over the image to visualize the pixel values corresponding to the areas to map, a pixel with the appropriate threshold value for that specific classification can be chosen. Once selected the appropriate threshold value, raster reclassification can be carried out with the *Raster Calculator* tool.

.....

6 https://grass.osgeo.org/grass76/manuals/i.pca.html

### 3.3.3.3 Polygon extraction and analysis

***Automatic raster to vector conversion***

The creation of vector polygons through automatic raster to vector conversion is the key process in the researched methodology. In QGIS this can be performed through the *Polygonize-raster to vector* tool, an algorithm based on the `GDALPolygonize` function that creates vector polygons for all connected pixel regions in the raster, i.e., that share a common pixel value. Optionally a mask band can be provided to determine which pixels are eligible for processing. Each polygon is automatically created and associated with an attribute that indicates the pixel value of that polygon. Polygon features will be created on a single output layer and will have the same georeferenced coordinate system as the image used (based on the geotransform of the source dataset). Each polygon can be associated with textual and alphanumeric information in the attribute table. The algorithm attempts to minimize memory usage so that very large raster's can be processed. However, if the raster has many polygons or if those polygons are very complex, the memory usage to hold the polygon enumerations and active polygon geometries can grow to be quite large. The algorithm generally is used to produce very dense polygon geometries, with edges that exactly follow the boundaries of all connected pixel edges. The algorithm is primarily intended for relatively simple thematic images such as binary masks, and classification results.

***Construction of topologic space and correction of topologic incoherence***

Topology[7] is the science investigating qualitative properties of geometrical figures – i.e. spatial relation properties – allowing to obtain specific qualitative definitions of space, which offer a more efficient analytic filter, based on its intuitive knowledge. In GIS technology, spatial relation representation and elaboration are widely used, given that in this sector the spatial relation between bodies is just as relevant as the bodies. In GIS, topology suggests the manifestation of spatial relations between geometric primitives, typically area vicinity and connection between lines.

7 The term "topology" was used for the first time in 1847 by J.B. Listing in his book Vorstudien zur Topologie (Introductory studies on topology). But the official birth of the branch of mathematics, which today we call topology, was thanks to Jules-Henri Poincaré (1854-1912) with his volume Analysis Situs (literally Analysis of position) published in 1895. Cfr. DI CRISTINA 2001, 7-13.



A possible classification of spatial relationships suggests their division into 4 sets:

1. topological relations that describe neighborhood and incidence (e.g., disjoint);
2. direction relations that describe order (e.g., north, northeast);
3. distance relations such as far and near, comparative or ordinal relations that describe inclusion or preference (e.g., in, at);
4. fuzzy relations such as next to and close [140].

ROI interest areas present on the artifact can be considered as related sub-sets defining a topological space in which the formal contents corresponds to the spatial value. Studying ROIs in topological space allows to describe meanings and relations between them starting from the extraction and filing phase.

Table 3.5
Example of the main topological relations.

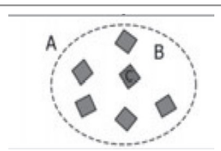
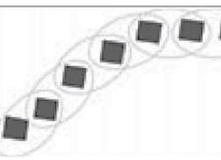
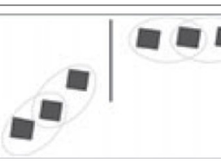
| GRAPHICS | TOPOLOGICAL RELATIONSHIP | DESCRIPTION |
|---|---|---|
|  | Proximity- Nearness | Spatial condition existing between separate but nearby objects.<br>The set A includes C and the neighborhood B of C (The points B-near C) |
|  | | |
|  | Succession | Spatial condition existing between separate objects placed to form a row. |
|  | Continuity | Spatial condition existing between objects belonging to each other's neighborhoods and therefore in a relationship of continuity. |
|  | Discontinuity | Spatial condition of interruption between two continuities |
|  | Internal-External | Spatial condition existing between objects placed in one of two regions of the plane, internal or external, divided by a closed line that delimits the boundary or area. |

Figure 3.31
Example of the main topological relations whit the topological primitives

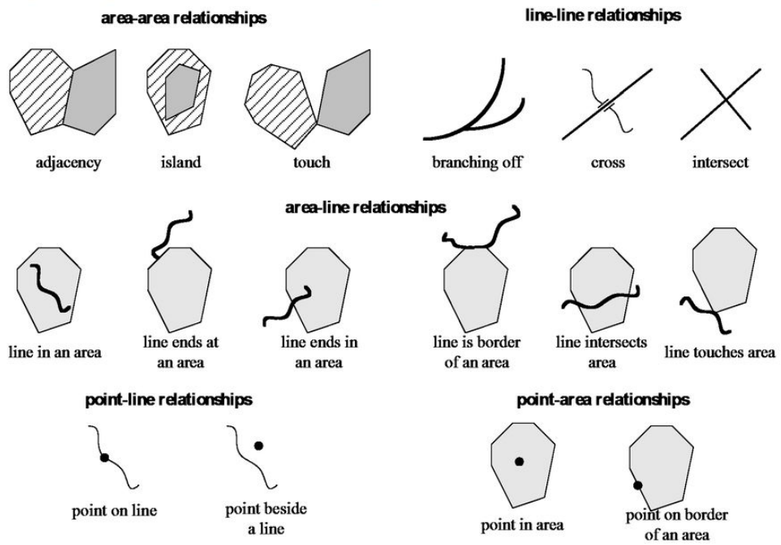



Figure 3.32
(a)Example of incongruence between lines.
(b) Example of incoherence between two areas, in this case the assumption of adjacency is not respected.

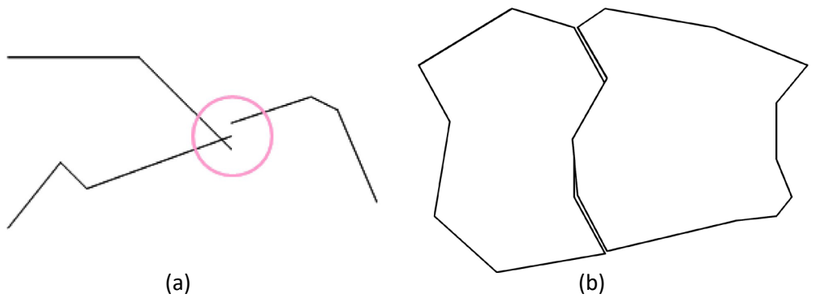
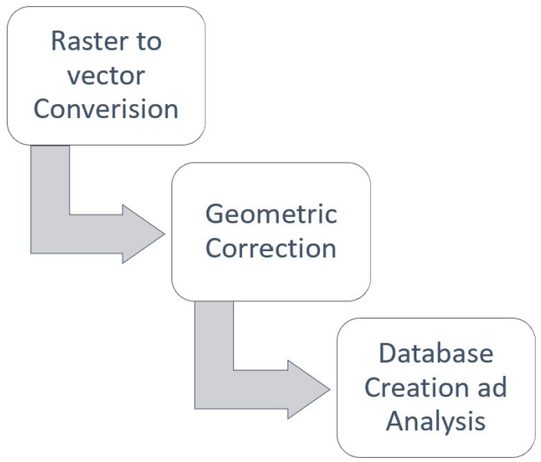



Figure 3.33
Sequenced process to obtain a database with topologically correct polygons.






***Correction of topologic incoherence***

Topological primitives are arch and knot, corresponding to geometric primitives line and point. Primitive area in the topological world is called “face”. To obtain a correct topologic superstructure, data must be consistent and not present topological errors, thus creation of topologic space is based on a first phase of data verification and correction from a geometric point of view. To obtain geometrically correct data, two touching areas should be “neighboring”, meaning that between them, along the contact line, there should be neither empty spaces nor overlapping areas. Similarly, two lines must be perfectly joint in the same vertex point and not present any overlapping or empty spaces before the vertex (Fig. 3.32 a). In the regions’ digitalization process, this neighboring is not necessarily respected in all layers and there can be polygons which present small overlapping areas or small void areas between two neighboring polygons (Fig. 3.32 b). Such inconsistencies do not represent a mistake from a geographical point of view, however they are not tolerated in a mathematical and IT sense because they lead to contradictory results and errors in statistic calculations. The aim of a topological approach is to solve this kind of inconsistency.

For the above reasons, an assessment of the errors present in polygons should be carried out before doing any kind of statistical analysis or further construction of topological relation tables.

QGIS offers various plug-ins for validation and correction of topological mistakes, two of which are integrated in the core: *Topology Checker Plugin*[8] allows to see a list of errors on all project layers; *Geometry Checker Plugin*[9] allows to check and correct a single layer’s geometric validity. Once the list of errors is acquired, correction can be carried out even by hand by enabling the *Topological Editing*[10] button and selecting what to correct; modification can be applied also involving different layers, as long as they are visible and in modification mode. Alternatively, the Grass[11] *v.clean* tool in QGIS can be used, which allows users to automatically

8 https://docs.qgis.org/3.10/en/docs/user_manual/plugins/core_plugins/plugins_topology_checker.html

9 https://docs.qgis.org/3.16/en/docs/user_manual/plugins/core_plugins/plugins_geometry_checker.html

10 https://docs.qgis.org/3.10/en/docs/user_manual/working_with_vector/editing_geometry_attributes.html

11 https://grass.osgeo.org/grass76/manuals/v.clean.html

find and correct vectorial maps' topology: a list of various operations to be carried out in sequence can be made by setting different tolerance and value parameters for each error.
Neighborhood between polygons of the same layer can be respected by using binary masks for the raster to vector conversion of regions of interest, so as to speed up some operations and at the same time keep control over possible errors.

***Statistics Analysis with the Field calculator***

A very important aspect of GIS systems is the possibility to carry out advanced statistical analysis on data. The tool used to carry out statistical analysis on polygons is the *Expression* function, present within the *Field calculator* tool. This tool allows to carry out calculations based on existing attributes values, and specific functions can be written to carry out different operations, such as geometrical elements' length or area calculation, percentage of one area compared to another etc. Results can be saved in a new field of the table of attributes, or they can be used to update values in an existing field. It's possible to choose from a list of preset functions relating to color, geometry, mathematical calculations, registration etc. Personalized functions can be defined with the Functions Editor, the editor creating new Python files which will be automatically uploaded at QGIS launch.

### 5.3.3.4 Advanced Tool for layout and print

The possibility offered by QGIS to layout thematic maps is one of the reasons why this software is the only one satisfying all needs of the proposed research.
In fact, QGIS features a layout and print window with advanced functions, any element or attribute present in the project can be added as an image, map, diagram, table or legenda. Furthermore, text labels, images external to the project, scaling bars, basic shapes, arrows, tables of attributes and HTML frames can be added. Each element can be resized, grouped, aligned, positioned and rotated, modifying its properties. The final map can be printed or exported in different image formats, PostScript, PDF or SVG. The layout can be saved as model and uploaded again in a new session. Finally, different maps based on one model can be generated through the *Atlas generator* tool, allowing to create different Layouts for each layer of the project. Thanks to the DataPlotly [12] Plugin – developed by Italian company Faunalia - all statistical analysis made can be exported in the Layout page as completely interactive diagrams connected with the elements placed within the thematic map itself: by clicking or selecting an element of the diagram, the connected map elements are selected. DataPlotly allows to create many different kinds of diagrams, and each kind of diagram can be customized in many ways. Beyond the possibility of creating a single diagram, diagrams (even of different kinds) can be overlayed, or even they can be placed in an actual grid. DataPlotly uses the constantly developing and updated JavaScript Plotly library. Thanks to various API, Plotly can also be used with other programming languages (Python, R, NodeJS, etc.). Each diagram comes with the raw html code with which it was made: thus, users can easily insert the diagram in an html frame. Furthermore, diagrams can be saved as static images (png) or as html files: the latter preserve interactivity, thus being easy to question. Currently, the plug-in is available in English, Italian, Dutch, Swedish and French.

12 https://www.faunalia.eu/it/dev/dataplotly

# CHAPTER IV

# Methodological approach and practical application

After the evaluation and experimentation of the chosen algorithms and software, a sequence of operations was defined that proved to be functional for the purposes of the research. Therefore, it was possible to realize a semi-automatic methodology divided into two phases and seven steps.

***Phase I***

The first phase is focused on image acquisition and processing, it includes four stages:

***1.*** Image acquisition- including instructions on methods of acquisition.

***2.*** Segmentation of the acquired images- with relative choice of channels that highlight the categories and classes determined by the restorer.

***3.*** Binarization of the chosen channels- with relative morphological operations of shape cleaning.

***4.*** Automatic conversion from raster to vector of the regions of interest (ROI) obtained with the binary masks.

Stages 2 and 3 can be performed in both QGIS and Matlab. Stage 4 can be performed in QGIS only.

***Phase II***

The second phase is dedicated to the processing of the recognized regions of interest and the extracted vector polygons and includes three stages:

***5.*** Database creation- with relative polygon characterization, attributes creation, ROI subdivision into layers, categories, classes and legend creation.

***6.*** Statistical evaluations of ROIs- measurements, percentage calculations, restoration cost assessments and risk assessments.

***7.*** Layout, archiving and printing of thematic mappings- this last stage involves the creation of the actual final graphic documentation.

All stages of this phase can only be performed successfully in QGIS.

The following shows a general outline of the methodology and a table illustrating which stages can be performed in QGIS or Matlab.

Figure 4.1
Outline of Methodology

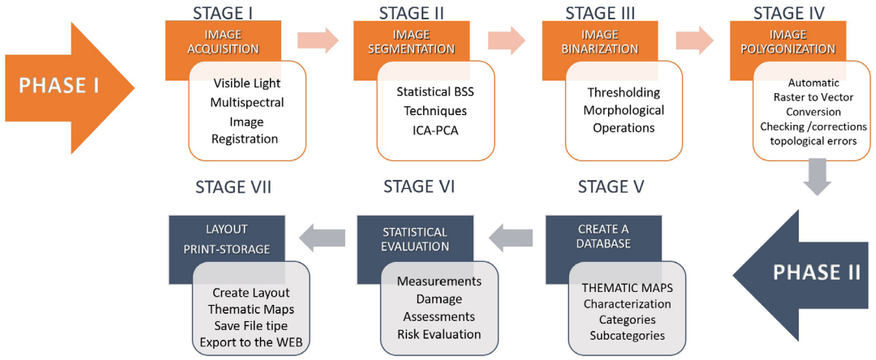



Table 4.1
Outline of Methodology

| PHASE I | | | |
|---|---|---|---|
| STAGE | | QGIS | MATLAB |
| STAGE I | IMAGE ACQUISITION AND INSERTING | X | X |
| STAGE II | IMAGE SEGMENTATION | X | X |
| | ICA | none | X |
| | PCA | X | X |
| STAGE III | IMAGE BINARIZATION | X | X |
| STAGE IV | IMAGE POLYGONIZATION | X | none |
| PHASE II | | | |
| STAGE V | CREATE A DATABASE | X | none |
| STAGE VI | STATISTICAL EVALUATION | X | X |
| STAGE VII | LAYOUT -PRINT | X | none |

# Section 4.1 PHASE I-STAGE I

## 4.1.1 Data Acquisition

First of all, we must analyze aspects concerning data acquisition to define precise guidelines and align the first methodology phase.

As opposed to esthetic, artistic or recreative photography, photographic documentation for cultural heritage must respect the correct documentation needs, i.e. it must be able to truthfully testify the artifact's visual material aspects, starting from the object's shape and its superficial morphology, up to its chromatic qualities. To be able to qualify as scientific analysis, acquisition results must reflect *consistency, measurability* and *reproducibility* criteria.

Consistency and measurability are to be intended as respect of formal and chromatic peculiarities, ensured through appropriate precautions taken while building the set and in the acquisition phase, which should be referenced in terms of colors and meters through calibration tools and standardized dimensional references. All this ensures the possibility of a correct post-production and digital color-correction of shooting data, from which images in line with the original subject can be gained.

Reproducibility of the shooting session must be guaranteed by filling out an activity report and a technical diagnostic report, to be kept both to verify methodology correctness and for further comparisons in time. Reproducibility should also be ensured by saving, cataloguing and archiving all original files and connected metadata, relating to all work phases.



Also, it must be stressed that one of the problems presented by a quantitative approach to the study of artifacts through digital images lies in the strong dependence of obtainable results by changing scale of analysis: in fact, reducing spatial resolution, information relating to the morphology of material features present on the surface is lost. So, for a complete characterization of the survey, it becomes necessary to work on images with a correct spatial resolution, in proportion to the artifact's size and to the enlargement level on which the analysis will be carried out. *Spatial resolution* indicates the amount of detail visible in it. As for our methodology, the main advantage consists exactly in the great number of available details, as each detail represents further information.

These principles apply to all image acquisition techniques, both in visible and multispectral light. Concerning the choice of diagnostic acquisition technique to be applied, this must be assessed by conservators/restorers or by researchers, and will have to be aimed at providing answers to specific (previously expressed) problems, and to questions concerning artifacts conservation and restoration, in their cultural and technological framework.

It is crucial that data obtained through the first acquisitions is accompanied by a careful interpretation of results, taking into account the profound chemical modifications which the artifact may have undergone since its realization, both in relation to its original materials and to the ones introduced in following interventions.

The following sections present some practical indications concerning equipment and acquisition procedure.

### 4.1.1.1 Equipment

Equipment to correctly organize a photographic set for diagnostics should include the following elements: acquisition system, support equipment, irradiant source, standard references and shooting accessories.

***Acquisition system*** when choosing a digital camera a *full frame* sensor is preferable, combined with a series of normal standard focal 35 to 60 mm lenses and with a limited wide-angle of 28 mm. Telemetric lenses and panoramic mosaic procedure are not advisable.

***The camera support system*** should have professional features, for example a three-way head allows better positioning in relation to the artifact, and a stable tripod with horizontal arm ensures a versatile construction in complicated sets. Also, the horizontal arm allows for higher quality images, thanks to a lower vibration impact, reducing the blurry effect. The bubble level is another necessary tool to obtain the camera's correct positioning.

***Irradiant sources*** should be assessed depending on closeness of the subject and the shooting technique, for example led panels present the advantage of a lower thermic dispersion, so they can be placed closer to the subject; they can be used in visible light, but not for reflected UV shooting. Warm halogen spot lights can be used both for visible light and for reflectography. It's important to always associate light sources to photographic umbrellas, both in reflection and in transmission to better control a uniform light diffusion. This characteristic must necessarily be maintained; in fact, reflections and not homogeneous light inevitably create "noise", disturbing the following phases of analysis and features extraction, deeply compromising the extraction's final result. To ensure homogeneous lighting, it is advisable to use a digital light meter, external to the camera.

***Standard exposition references*** are absolutely necessary both for color-correction and for the correct measurability of the acquired data. It's advisable to use a *color-checker* including both the chromatic part and the grayscale, or for stronger reliability a *Labsphere Spectralon* can be used.

### 4.1.1.2 Acquisition procedure

Acquisition procedure includes different moments, articulated as follows: camera positioning, set construction, precautions for shooting and data saving.

***Camera positioning:*** to devote the maximum sensor surface to the framed subject, the longest side of the artifact must coincide to the long side of the sensor. Thus, camera orientation should be defined based on the artifact, avoiding to include in the shot an excessive background portion or undesired surroundings.
To acquire the most orthographic shot in relation to the subject, the camera



should be placed in front of the artifact's center, as orthogonally as possible, even measuring a possible subject inclination on the sensor's vertical axis and adapting the camera to this inclination. If this operation is not possible, it's important to correct the image's perspective deformation in post-production.

***Set Construction:*** generally speaking, set indicates a structured environment to host the subject and acquire shots, eliminating disturbing light sources. The distance selected for the lighting sources and for the camera, in relation to the object, should be traced on the floor and registered in a shooting chart. Furthermore, it's important to register all the cameras' and lenses' technical features, so that set construction can be repeated.

***Shooting precautions:*** digital files can be saved in the camera memory in different modalities, distinguished by their ability to preserve data integrity. It's advisable to save images in RAW format, allowing a correct color-correction of exposition in post-production and to use a series of visualization settings defined as *Picture Control*. As for the camera color space, it's advisable to use RGB 1998, which is more complete than SRGB space. It's advisable to use the standard or uniform *Picture control* management, setting the *White balance* selection according to the light used. It should be stressed that HDRI (*High Dynamic Range Imaging*) can't be considered an accepted modality for correct cultural heritage documentation, as it produces an compensation artifact of high and low lights.

***Data saving:*** images acquired in RAW format require digital elaboration to be converted into delivery formats tiff and jpeg. The most common programs for this purpose are Camera RAW, integrated in the Adobe Photoshop packet and Adobe Light Room: the former allows to modify individual images, whereas the latter allows post-production of many related files contextually. Once all the images have been elaborated, and color-correction completed, files can be exported in the required formats. It's crucial that no compression is used and that Adobe RGB 1998 color space is selected.

## 4.1.2 Image Registration

Image data coherence is one of the fundamental requirements of the methodology. In order to proceed to the second phase concerning the application of segmentation algorithms, it is necessary that all the images acquired on the same artifact, in the same phase of the restoration intervention, are correctly registered with each other. Image registration is a technique used to align images of the same subject taken with different acquisition techniques. Alignment involves eliminating slight rotations and tilts and re-sampling the images to the same scale. It is not always possible to obtain full alignment of all acquired data because artifacts may change their morphology during the restoration intervention. In these cases, it is essential to provide consistency between sets of data acquired during the same phase of the intervention. This article [141] dating 2003 aims to present a review of recent and classical image registration methods. On the other hand, this more recent article [142] proposes a new image registration framework based on multivariate mixture model (MvMM) and neural network estimation. The phase of image recording is simultaneous to the phase of image inserting in QGIS and will be discussed in the relevant section 3.3.2.1.

### 4.1.2.3 Registration in Matlab

The recording operations can also be performed in Matlab software. The application is located in the *Image Processing and Computer Vision toolbox* and is called *Registration Estimator.* This application supports three groups of registration techniques:

***Feature-Based Registration:***

Feature-based registration techniques automatically detect distinct image features such as sharp corners, spots, or regions of uniform intensity. The moving image undergoes a single global transformation to provide the best alignment of corresponding features with the still image. The table below lists the functions available for this technique.

Table 4.2
Options of Matlab's Feature-based-registration tool.

| | |
|---|---|
|  | FAST detects corner features, especially in scenes of human origin such as streets and indoor room; supports single-scale images and point-tracking. |
|  | MinEigen also detects corner features; supports single-scale images and point-tracking. |



| | |
|---|---|
|  | Harris also detects corner features, using a more efficient algorithm than MinEigen; supports single-scale images and point-tracking. |
|  | BRISK also detects corner features. Unlike the preceding algorithms; supports changes in scale and rotation, and point-tracking. |
|  | SURF detects blobs in images and supports changes in scale and rotation |
|  | MSER detects regions of uniform intensity; supports changes in scale and rotation and is more robust to affine transformations than the other feature-based algorithms. |

***Intensity-Based Registration***

Intensity-based registration techniques correlate image intensity in the spatial or frequency domain. The moving image undergoes a single global transformation to maximize the correlation of its intensity with the intensity of the fixed image. The table below lists the functions available for this technique.

| | |
|---|---|
|  | Monomodal intensity registers images with similar brightness and contrast that are captured on the same type of scanner or sensor. For example, use monomodal intensity to register MRI scans taken of similar subjects using the same imaging sequence. |
|  | Multimodal intensity registers images with different brightness and contrast. These images can come from two different types of devices, such as two camera models or two types of medical imaging systems (such as CT and MRI). These images can also come from a single device. For example, use multimodal intensity to register images taken with the same camera using different exposure settings, or to register MRI images acquired during a single session using different imaging sequences. |
|  | Phase correlation registers images in the frequency domain. Like multimodal intensity, phase correlation is invariant to image brightness. Phase correlation is more robust to noise than the other intensity-based registration techniques. |

Table 4.3
Options of Matlab's Intensity-Based Registration tool.

***Nonrigid Registration***

| | |
|---|---|
|  | Nonrigid registration applies nonglobal transformations to the moving image. Nonrigid transformations generate a displacement field, in which each pixel location in the fixed image is mapped to a corresponding location in the moving image. The moving image is then warped according to the displacement field and resampled using linear interpolation. |

Table 4.4
Options of Matlab's Nonrigid Registration Registration tool.

## 4.1.3 Project creation in QGIS and image inserting

After having acquired the images, the next step is to create the project in QGIS. The procedures for creating the project are listed below.

### *Start QGIS*

QGIS can be started like any other application:

- using the Applications menu, the Start menu, or the Dock
- double clicking the icon in Applications folder or desktop shortcut
- double clicking an existing QGIS project file (with .qgz or .qgs extension). Note that this will also open the project.

At startup, a list of **Project Templates** and **Recent Projects** are displayed, including screenshots, names and file paths (for up to ten projects). The **Recent Projects** list is handy to access recently used projects. Double-click an entry to open the project or project template.

### *Creation of new project*

To start a new session, choose Project ► New.

Each project in QGIS has an associated **Coordinate Reference System (CRS).** The project CRS determines how the data is projected within the map in QGIS. Choosing an inappropriate CRS can cause map distortions and inappropriately reflect the sizes and positions of objects relative to the real world.

For small artifacts, buildings, or archaeological sites the appropriate projection is Pseudo Mercator, which in QGIS corresponds to two metric reference systems such as **WGS 84 Pseudo-Mercator / EPSG 3857 or EPSG 6871.**

- The CRS of the project can be set through the CRS tab of the **Project Properties** dialog box **(Project ►Properties).**
- It will also be displayed in the lower right part of the QGIS status bar; to access the Project Properties window just double-click on the icon EPSG:4326 in the lower right corner.



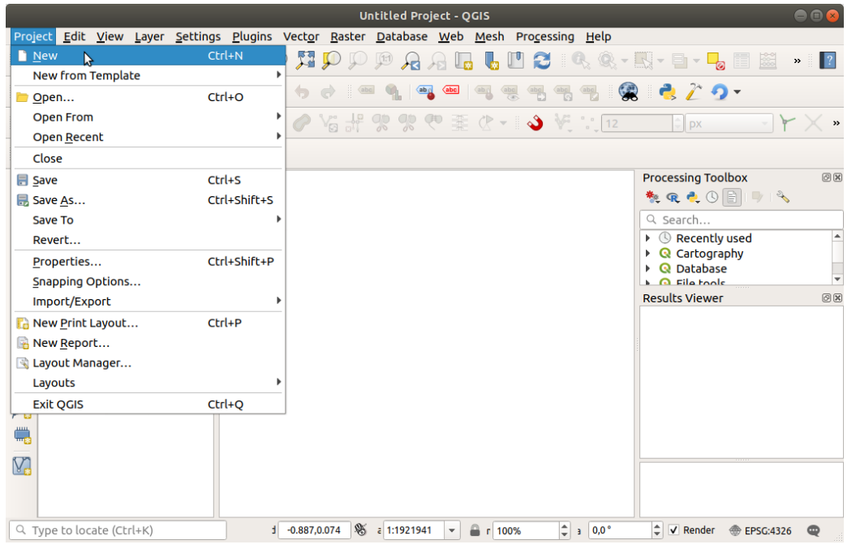



Figure 4.2
QGIS screenshot.
Creating a New Project

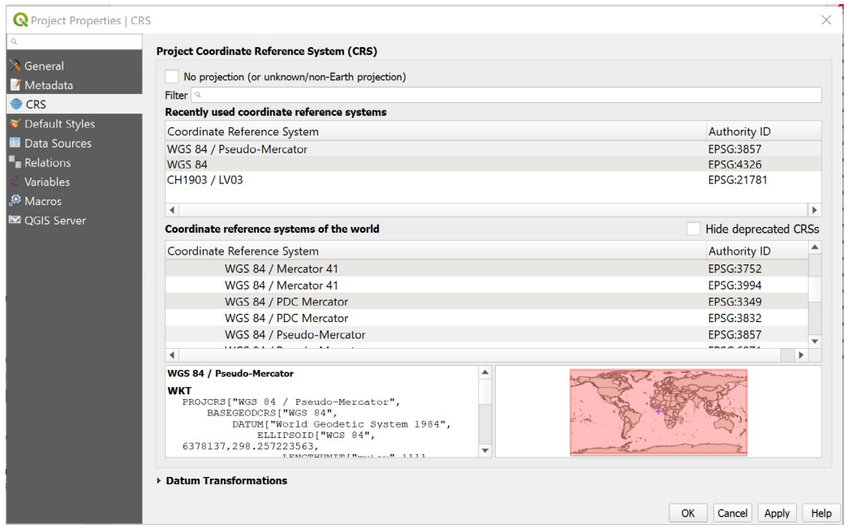



Figure 4.3
QGIS screenshot.
Project Properties window.
Choice of Coordinates Reference System.

### *Setting up images*

The insertion of images in QGIS must be preceded by two operations:

1. To uniform the images at the same spatial resolution and dimension in scale 1:1: each image- or group of images- must be assigned metric values in scale 1:1, that is the cm of the file must correspond to the real cm of the object. The spatial resolution must be the same for all images acquired. In order not to make the project too big, it is recommended to use maximum 300 dpi resolution.
2. Create the word file for each image (the word file topic was discussed in section 3.3.2.1). The word file can be created with any text editor.

The images and wordfile recorded in this way should be kept together in a single folder.

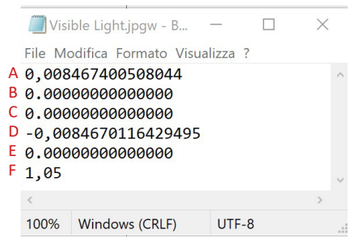



Figure 4.4
World File appearance

### *Inserting Images*

To load the files in QGIS:

- Click on the Open Data Source Manager icon. The **Data Source Manager** should open in **Browser** mode.
- Click the icon of raster and browse to the folder.
- Select only the raster file and double-click it. Multiple images can be added at once.
- The raster layers are added in the background of the project while the **Data Source Manager** window remains open.
- If the project settings are correct, each raster layer will automatically have the same **Coordinate Reference System** as the created project. If not, the icon will appear and it will be necessary to manually set the same **Coordinate Reference System** as the project.



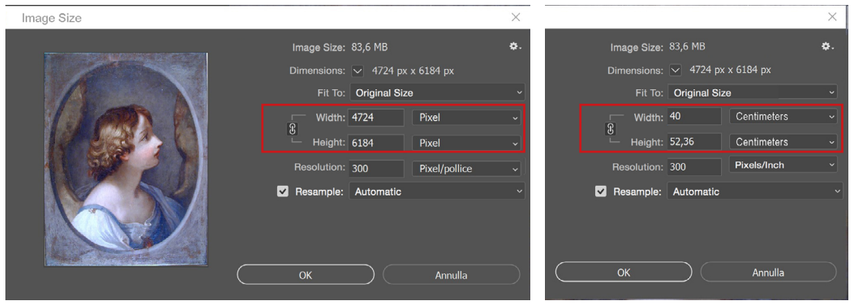



Figure 4.5
Photoshop screenshot. Image Size windows. Setting the image size to 1:1 scale, resolution 300. To calculate the A-value of the World File do the division of the width value in centimeters by the width value in Pixels. To obtain the value of E in the World file perform the same calculation for the height.

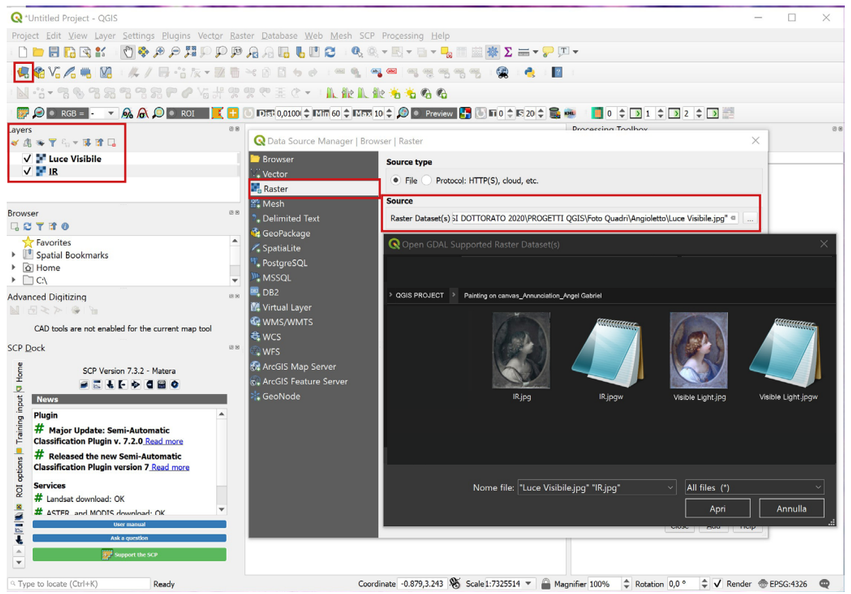



Figure 4.6

QGIS screenshot. Image insertion process. Data Source Manager window

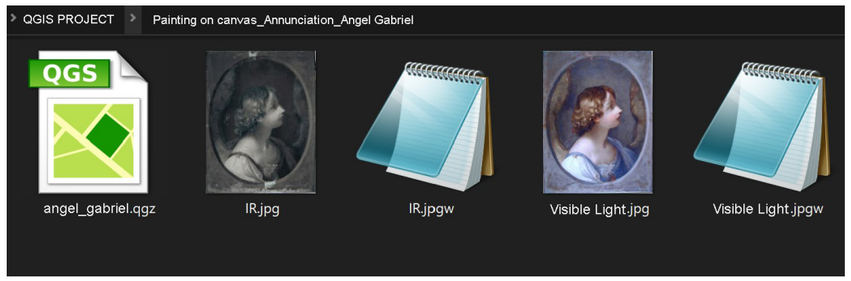



Figure 4.7
Screenshot of project folder. Aspect of QGIS Project, images and respective worldfile recorded in the same folder.

### *Co-registration of image*

Image registration can be refined with the Geo-Referencer, a tool that allows using control points, like markers, to make the pixels interior of the raster coherent with each other. Based on the transformation parameters and the number of points used, the plugin calculates the parameters and registers the images and the internal morphology of the figures. It is important to choose recognizable points in both images.

The first step is to load the Georeferencer Plugin in the Plugins dialog. Then the plugin appears in the QGIS menu bar; click **Raster ►Georeferencer.** The Georeferencer Plugin window appears as shown in figure. 4.7-8.

- To start georeferencing, it is necessary to upload the raster file again using the button. The raster will be displayed in the main workspace of the dialog.
- By selecting the Add Point button, the mouse icon will change into a cross.
- Click on a point in the raster image and choose the **From Map Drawing Area** button to add X and Y coordinates by selecting a point from the reference raster- already inserted into the project with the world file system.
- With the button it is possible to move point in both windows.
- It's necessary to enter a minimum number of 3 points but the more points are entered, the better the result will be.
- The points added to the map are saved in a separate text file ( [filename].points) together with the raster image; reusing the Georeferencer plugin later it' s possible to use the same points on a different raster. The points file contains values of the form: : mapX, mapY, pixelX, pixelY. A button can be used to load points Load GCP points and to save them the button Save GCP points as.
- Once GCPs have been added, it is necessary to define the transformation settings of the georeferencing process. Several transformation algorithms are available, in our case it is important to use the **linear transformation** algorithm as it does not operate any deformation of the original raster- the only operations it operates are resizing or translation. Among the re-sampling methods, the **nearest neighbor** equally does not change the BIT structure and



pixel value but only moves them.

- Finally, select Load into QGIS when finished to automatically load the output raster into the QGIS project when the transformation is complete. Figure 4.8 shows the transformation window with the right settings.
- After all points have been registered and all transformation settings have been defined, just press the Start Georeferencing button to create the new georeferenced raster layer.

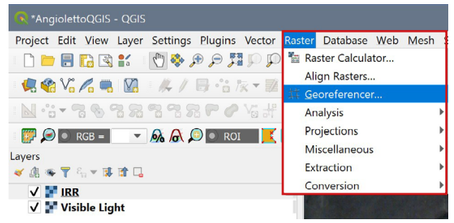



Figure 4.8
Screenshot of project folder. Aspect of QGIS Project menu bar.

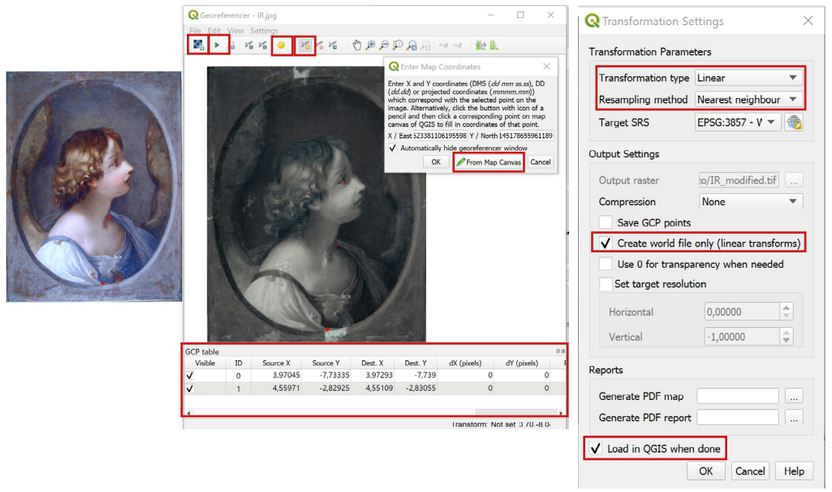



Figure 4.9
Screenshot of the Georeferencer Plugin window and the Transformation Parameters.

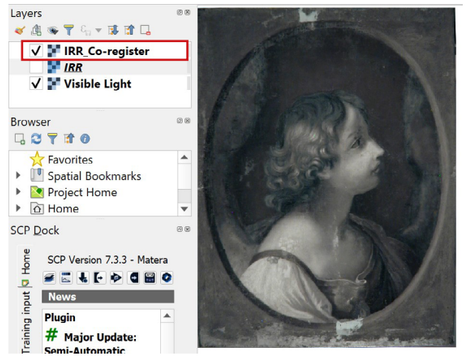



Figure 4.10
Screenshot of project folder. Project window with loaded and co-registered raster layers.

# Section 4.2 PHASE I-STAGE II

## 4.2.1 Image Segmentation

After registering the images with each other and creating the project in QGIS it is possible to advance to the second stage of the methodology that involves the first passage in image segmentation process using BSS Blind Source Separation techniques. Usually the available diagnostic images are analyzed by the operator visually and separately, our strategy is to consider the entire set of images by combining all the recorded images in a single multi-band raster file.

### 4.2.1.1 Segmentation in QGIS

In QGIS it is only possible to perform the PCA algorithm as the ICA algorithm has not been implemented at this time. Pca is present in three tools, i.e. **Grass's i.pca** in the list of processing tools, the plugin **PCA4CD - PCA for change detection** and finally the **Semi-Automatic Classification Plugin.** It is recommended to use the latter because it presents a complete and accessible documentation.

***Semi-Automatic Classification Plugin***

- Before proceeding with the execution of the PCA it is necessary to download and activate the Plugin inside the Plugins dialog window (Fig. 4.11).
- Subsequently it is necessary to merge all the images into a single multiband raster. To perform this operation, select from the top menu bar **Raster ►Miscellaneous ►Merge.** In the dialog box select the images to merge and check the option ***place each input file in a separate band*** (Fig.4.12).

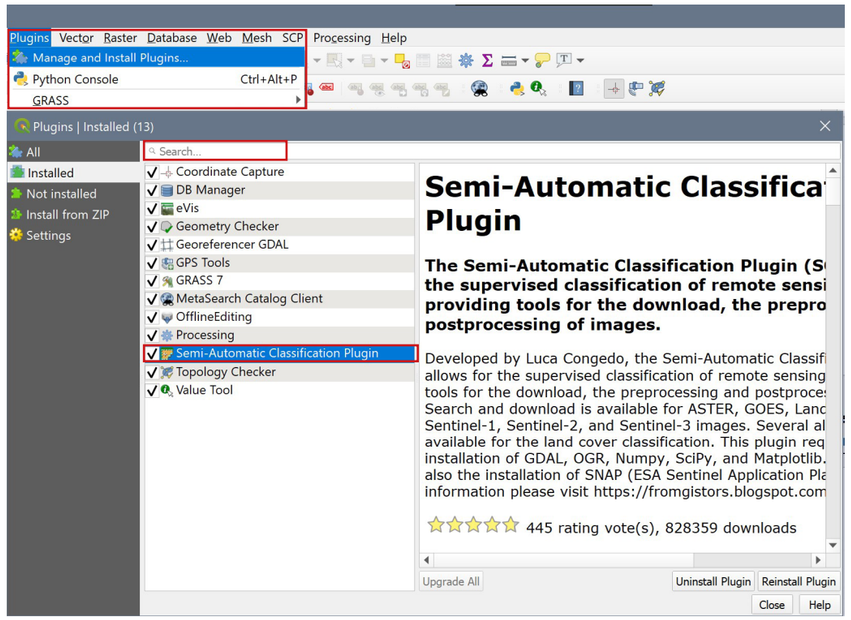



Figure 4.11
Screenshot of Plugins dialog window in QGIS.

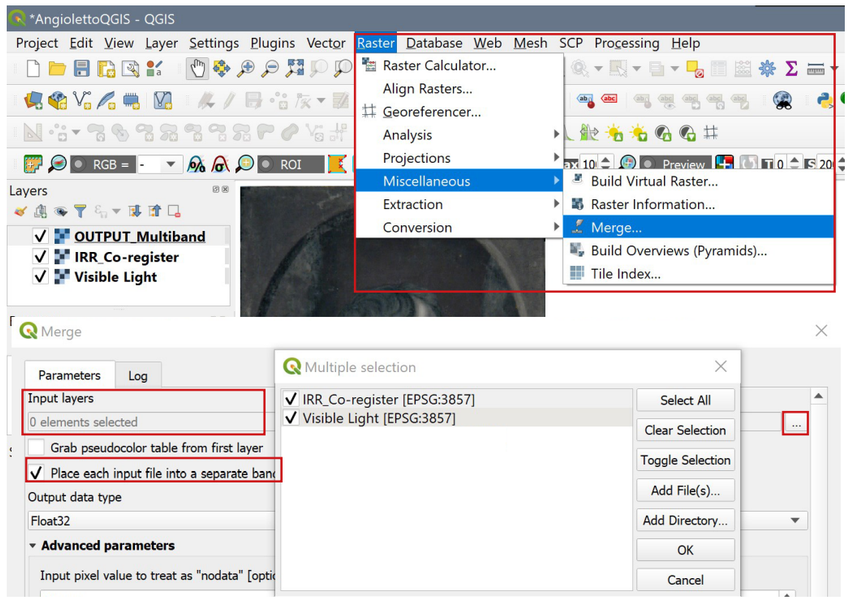



Figure 4.12
Screenshot of the dialog window for merging the rasters into a multiband image.

- At this point the **Semi-automatic classification Plugin (SCP)** window can be opened, select the **Band Set** menu item, load the multiband raster layer and select all bands as shown in the figures 4.13.
- Subsequently, select the menu item **Band Processing ►PCA**. Choose the save folder for the outputs and set the dialog box as shown in figure 4.14. Then click on RUN. The PCA outputs will be automatically loaded in separate layers.

***Generate the Pseudocolor***

To generate a pseudocolor from the PCA outputs, choose the outputs that emphasize the characteristics searched and repeat the Merge operation. The example is shown in figure 4.16.

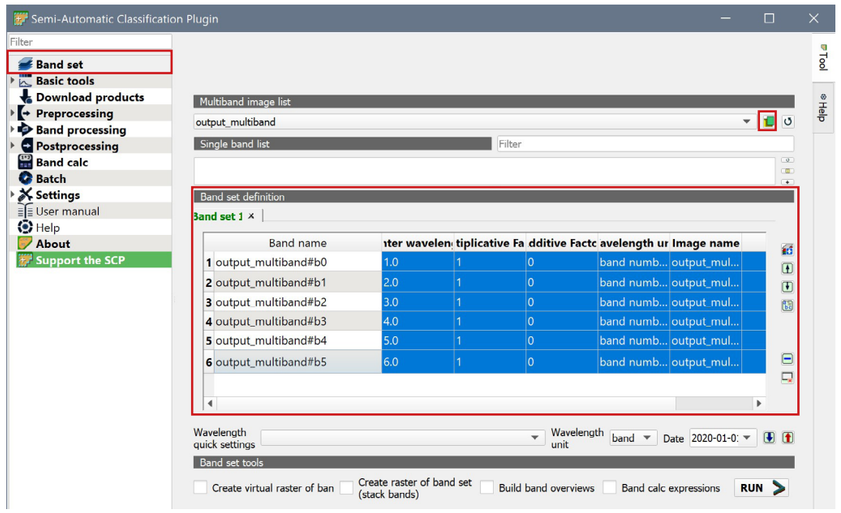



Figure 4.13
Screenshot of the dialog window of Semi-Automatic Classification Plugin.
Load a Band Set.

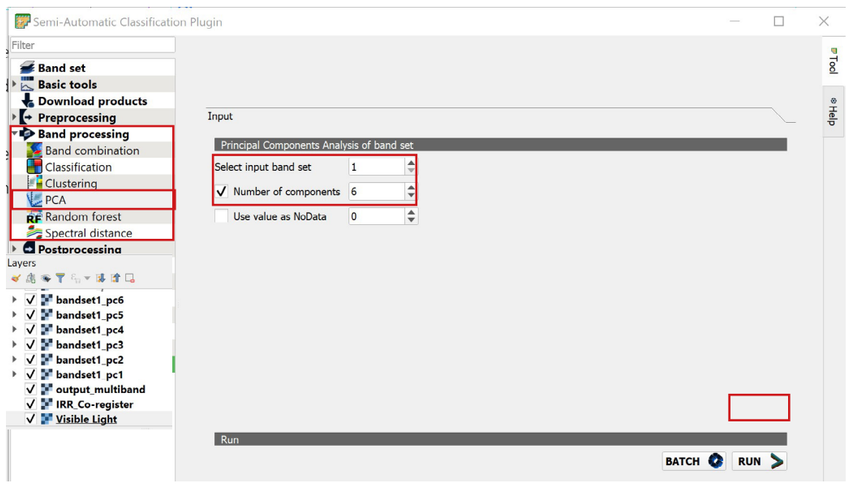



Figure 4.14
Screenshot of the dialog window of Semi-Automatic Classification Plugin.
Processing PCA of the Band Set Loaded.
Choose the number of channels/Component to output.



Segmentation can be emphasized by using a tool that, by working on the histogram, allows to make areas more contrasting with each other. To activate the tool select **View ►Toolbars ► Raster** from the menu bar, these icons will appear.



Starting from the left, the first four icons work on the histogram, the following ones on the brightness and contrast of the image.



(a) (b)

Figure 4.15
Example of histogram cut stretch applied on pca output.
(a) Original PCA.
(b) Streched using second icon of toolbars Raster.

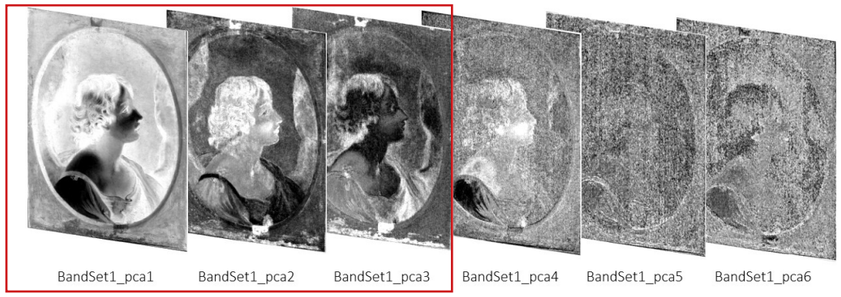
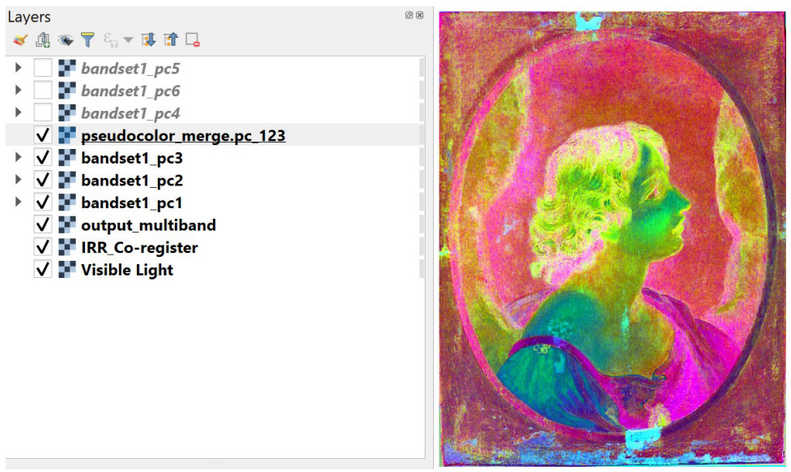



Figure 4.16
PCA extracts from Semi Automatic classification Plugin. The first three outputs were joined with the raster merge option to form a pseudocolor.



### 4.2.1.2 Segmentation in Matlab

Even though the Matlab software does not allow to perform all the steps of the methodology, its use is very useful in the image segmentation phase. This section shows the use of the applications mentioned in section 3.3.1.

***Image Processing and Computer Vision***

***App Image Segmenter***

From the MATLAB® toolstrip, open the Apps tab.In the Image Processing and Computer Vision section, click **Image Segmenter**.

- To start, load an image with the load image tool . Once the image is loaded, three toolboxes will be active.
- The first box contains three tools for thresholding - the first Treshold is only available for grayscale images. The second Box contains three tools for adding or deleting pixels from the mask. The third Box contains five tools for refining the mask.

*1. Box to segmenter*

- **The threshold tool** is very useful in its manual option. The dialog contains a slider to manage the threshold tolerance (Fig. 4.18).
- To use the **Graph Cut tool** , you need to mark foreground and background objects by drawing segments or points on the image. Also in this app the approach is iterative, it is possible to refine the segmentation by deleting some lines or by using the side slider **Subregion Density** to perform dilation or erosion of the mask. It is recommended to perform the latter while viewing the selection as a binary mask (Fig. 4.19)
- The **AutoCluster** tool has no dialog, it automatically creates a selection.
- **Find Circles** is not useful for the scopes of the search in that it only segments circular objects.

When the desired mask is obtained click on the **Create Mask** icon present in each dialog. The obtained mask will be loaded in the app's dialog box in the history section.



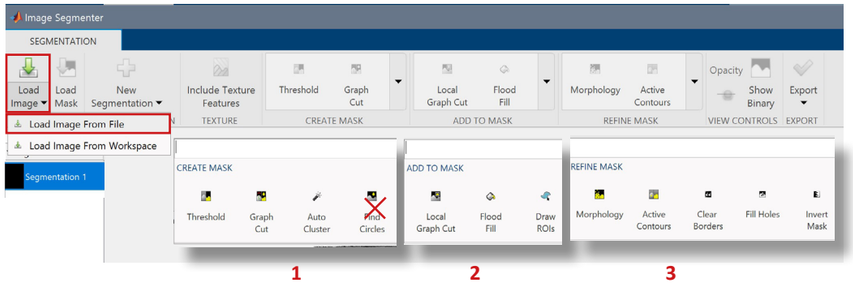



Figure 4.17
Screenshot of Matlab. Dialog window of Image Segmenter.

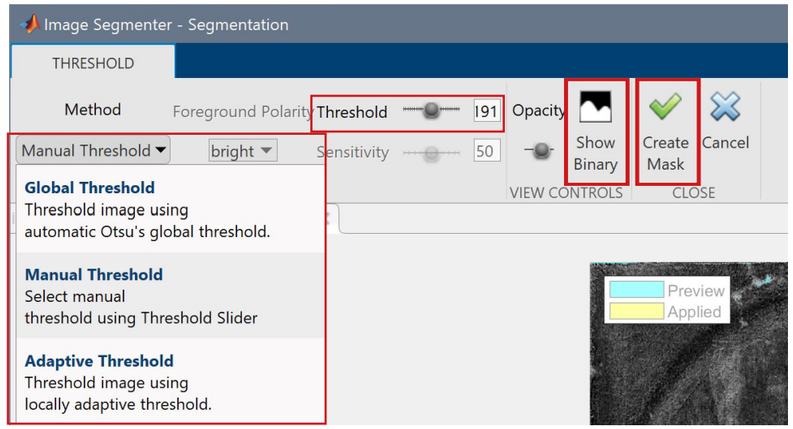



Figure 4.18
Screenshot of Matlab. Dialog window of Image Segmenter. Threshol app.

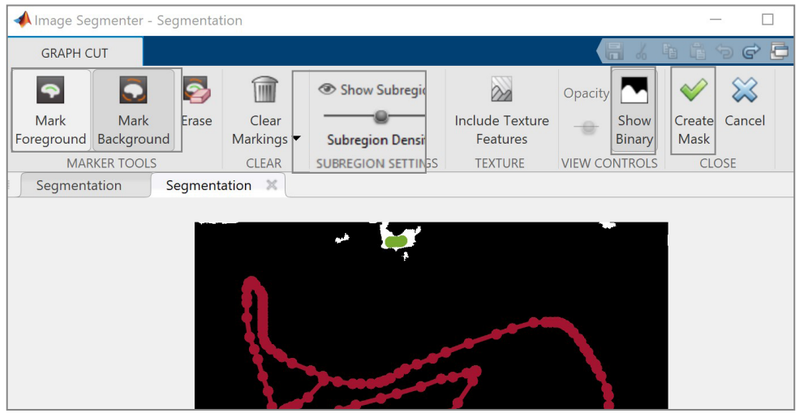



Figure 4.19
Screenshot of Matlab. Dialog window of Image Segmenter. Graph Cut app.

*2. Box for adding pixels:*

- In this box the only really useful tool is the **Flood Fill** . With the bucket tool it is possible to add areas to the mask with a simple click. In addition, the metric tolerance distance adjustment feature makes this procedure iterative.
- **Draw ROI** is useful for adding areas to the mask that don't have homogeneous pixels or clear edges. It allows users to draw the outline manually and add the drawn area to the mask.

*3. Box for refining the mask:*

- In this box the only useful tool is **Morphological operations** ; it is ideal for optimizing the selection made. From the drop-down menu it is possible to select the type of operation to be performed and the shape to execute it.
- **Fill Holes** does not have a dialog box but only allows automatic filling of small holes in foreground regions.

Every mask and pixel selection extracted and optimized has to be exported into the **Matlab Workspace**. In addition to the mask and the image, it is also possible to export the function used to generate it.

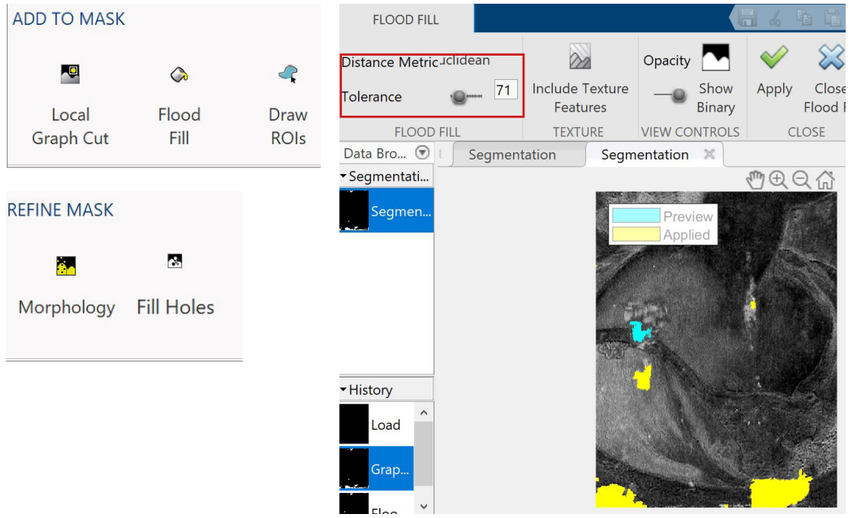



Figure 4.20
Screenshot of Matlab.
Dialog window of Image Segmenter.
Food Fill tool for add to mask.



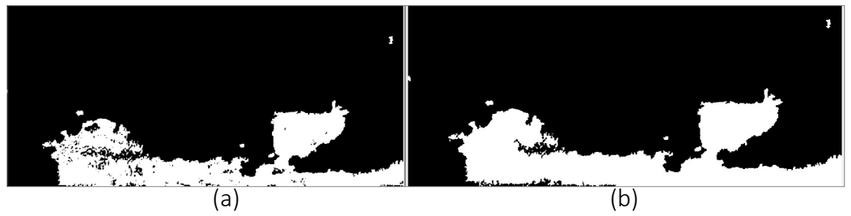



Figure 4.21
Screenshot of Matlab.
Dialog window of Image Segmenter.
Fill Holes tool.

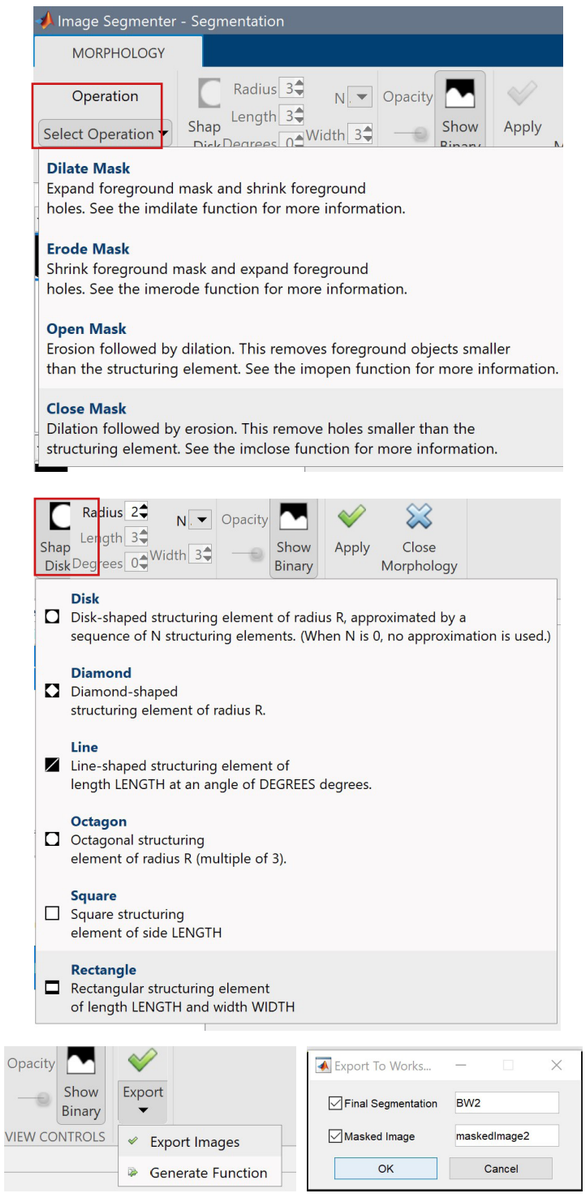



Figure 4.22
Screenshot of Matlab.
Dialog window of Image Segmenter.
Toll to Export the image and Binary Mask and Generate Funciotn.

*Image Processing and Computer Vision*

*App Color Thresholder*

From the MATLAB® toolstrip, open the Apps tab.In the Image Processing and Computer Vision section, click **Color Thresholder**. This application can only be used to segment color images.

- To start, load an image with the load image tool. Once the image is loaded, the image is displayed together with four color models to choose from for segmentation.

Clicking on the desired color model will open the interactive window for segmentation. The app reproduces the image in three types of representations: photo, 3D color space, histogram for each channel.

- The three versions of the image are shown simultaneously in one working window and it is possible to perform segmentation in several representations at once (Fig. 4.24). It is recommended to use the HSV space.
- In this case to generate the selection it will be possible to move the cursors in the respective histograms H,S,V.

Analogous to the image segmenter app, it is possible to view the result of the binary mask and export it along with the function.

To perform finishing operations on the binary mask extracted with this application it is necessary to load it into the **image segementer** application.

All binary masks and segmented images can be exported from Matlab.

- To perform this operation select the **image View** app. The Image Viewer application allows to interact with images and save them in different formats
- Load an image from the Workspace and then click Save as to save it (Fig.4.25).

In Matlab it is also possible to operate the **FastICA** and **PCA** algorithm, this topic was discussed in section 3.3.1.2.



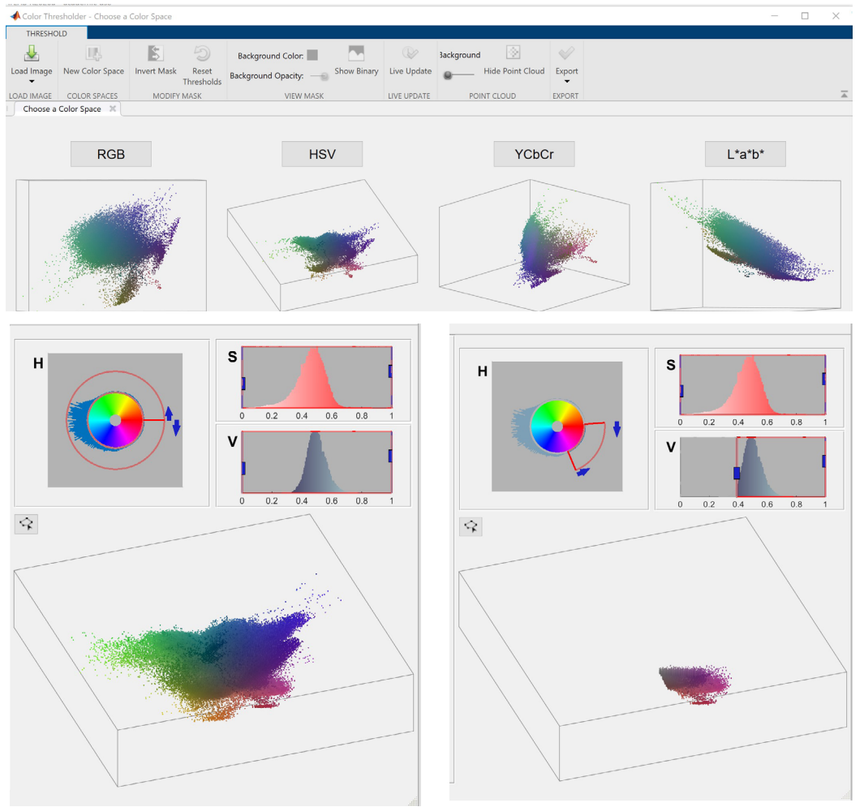



Figure 4.24
Screenshot of Matlab. Dialog window of Color Thresholder Toll.

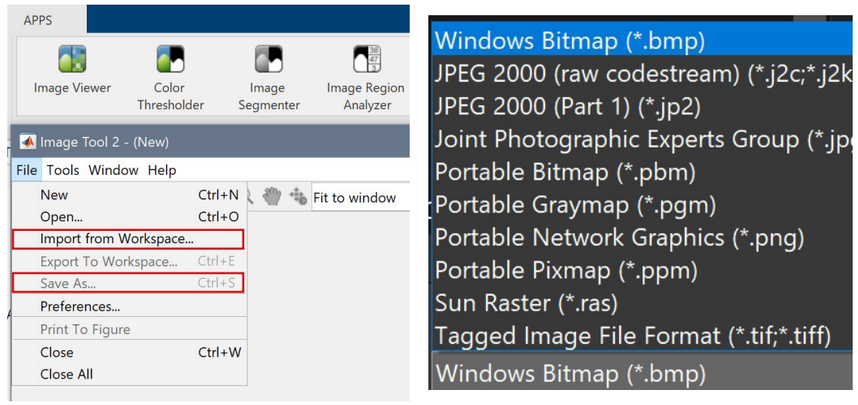



Figure 4.25
Screenshot of Matlab. Dialog window of Image Viewer.

# Section 4.3 PHASE I-STAGE III

At this stage, the operator chooses the output images in which the features researched are most evident. It is worth to point out that the choice of the output image from which to extract the binary masks is the responsibility of the restorer. This choice is necessary in order to filter only the are of interest ROI for the specific class of features to be mapped. A completely automated execution of all outputs results in the identification and selection of unwanted regions.

## 4.3.1 Binary mask extraction

After choosing the images, the binarization can be done.

### 4.3.1.1 Binarization in QGIS

**The fastest tool in QGIS for classifying pixel values and extracting binary masks is the Raster Calculator tool which allows to perform calculations based on pixel values. Before performing the binarization it is necessary to choose a threshold value.**

- Add the **Value Tool** plugin, select the tool icon and enable it in the reference window. In the same dialog choose the band on which to do the evaluation.
- By simply scanning over the image the value of pixels will appear in the window. Focusing on the pixels corresponding to the respective areas to be mapped, choose the pixel with a threshold value appropriate for that specific classification.
- Once decided the threshold value, proceed to raster reclassification with the **Raster Calculator** tool.
- Under Processing tools select the **Raster calculator** item.Inside the dialog there is a box called **Raster Bands list** which contains all the raster layers loaded in the project.
- To choose the raster to edit and add it to the **expression field** of the raster calculator, double-click on its name in the Fields list (Fig.4.26).
- At this point it is possible using operators to build calculation expressions or manually typing them in the appropriate box.
- The expression to write in order to obtain the binary mask is as follows:

```
("bandset1_pc3@1"<-45)*1+("bandset1_pc3@1">=-45)*0
```

where 45 represents the threshold value.
In this case values less than 45 will be classified as value 1 and values greater than and equal to 45 will be classified as value 0.

- Before performing the classification, it is necessary to choose a folder for saving the binary mask.
- The binary mask is loaded to a new raster layer. Perform the same operation on each chosen PCA output.

The expressions can be saved and reused. For each PCA output it is possible to choose a different threshold value or to perform different tests changing only the threshold value, until the desired result is reached.
The result is a set of binary masks that identify ROIs and will facilitate subsequent steps.

### 4.3.1.2 Binarizzazione in Matlab

The apps used for segmentation include automatic extraction into binary masks of the resulting data. Masks created in Matlab and saved with the Image View app can be imported into QGIS to perform the next steps of the methodology.

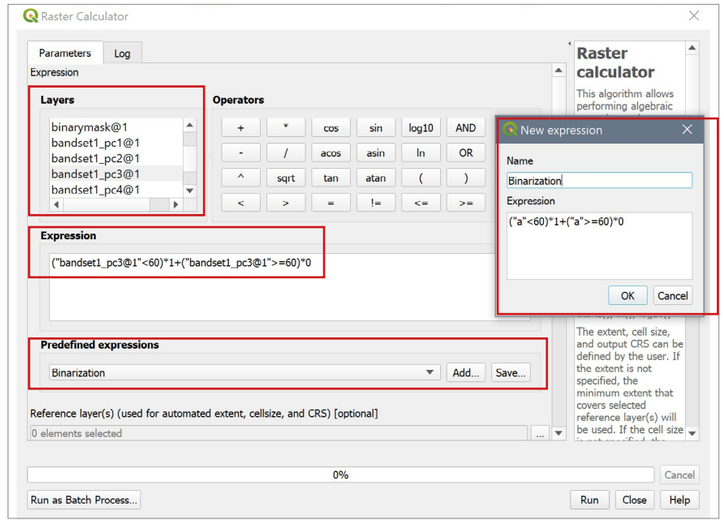



Figure 4.26
Screenshot of QGIS raster calculator panel.

# Section 4.4 PHASE I-STAGE IV

## 4.4.1 Raster to vector conversion

The raster to vector conversion of the Regions of Interest (ROI) extracted is the key to the methodology: it represents the only but fundamental automatic step. The process of transformation from raster graphics to vector drawing is currently done through the use of subjective "filters" such as the operator's personal skills in digital drawing. The person who performs the drawing outlines the areas of interest following the boundaries dictated by his experience and visual perception and especially by his patience. Automatic conversion speeds the process of creating thematic maps and makes the drawing geometrically correct and objective. As described in section 3.2.3 and 3.2.4, to obtain an optimal result the raster to vector conversion must be performed only on binary images, not in grayscale or color. Moreover, before converting, it is recommended to refine the binary mask through morphological operations and to close small holes present in the areas. This step of the methodology also marks the transition from the first to the second phase: all subsequent operations will be exclusively focused on the manipulation and analysis of vector polygons.

In QGIS the conversion can be performed by selecting in the top menu bar the item **Raster►Conversion► Polygonize (Raster to Vector).**

This algorithm is based on the **GDALPolygonize** function that creates vector polygons for all connected pixel regions in the raster, i.e., that share a common pixel value(Fig.4.29).

At the end of the conversion a new polygon layer is created that contains the polygons relative to the areas with value 0 and those with value 1. Before proceeding with the following operations, it will be necessary to eliminate the polygons relative to the background.

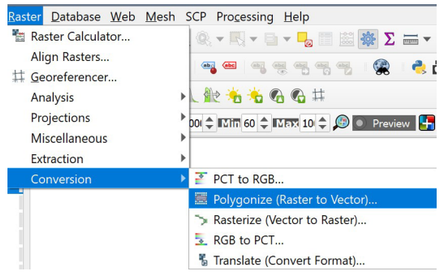



Figure 4.27
Screen Shot of QGIS. Raster to Vector conversion tool.

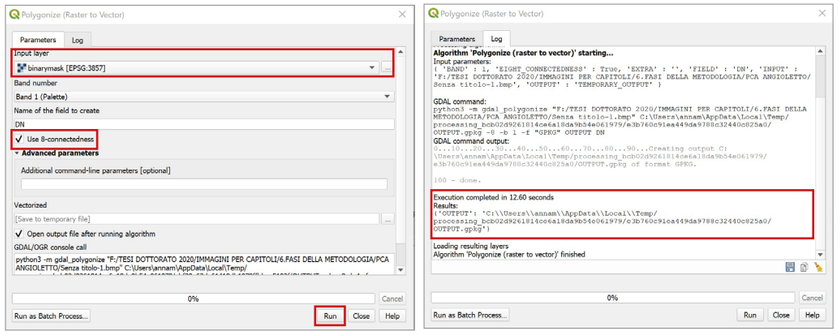



Figure 4.28
Screen Shot of dialog window of Raster to Vector conversion tool.

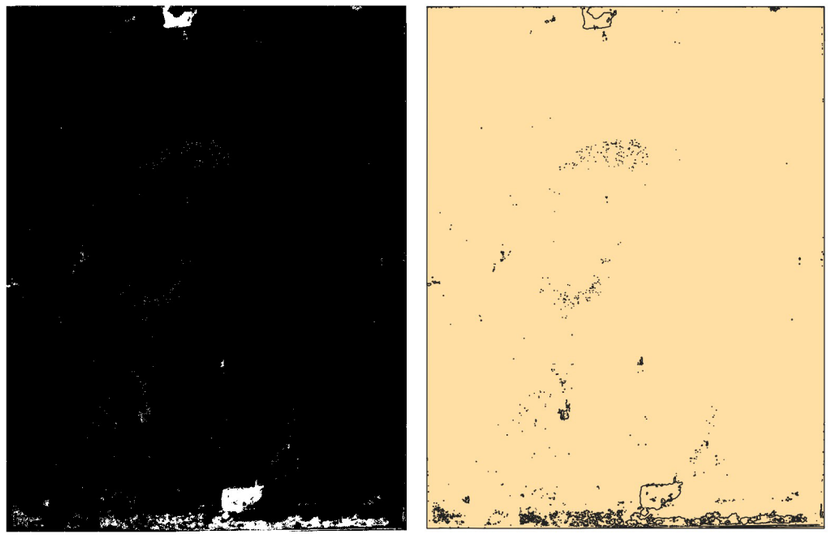


Figure 4.29
These figure shows the appearance of the automatically extracted polygon layer.

- To delete background polygons right-click on the polygon layer and select **Open Attribute Table**.
- Check the **Pencil** icon to activate the Editing.
- Then filter the view of the polygons by selecting **Field Filter►DN** from the drop-down list (Fig. 4.30).
- In the appropriate bar write the value of the pixels on the background that are intended to be eliminated. Usually the value 1 corresponds to the ROI and the value 0 to the background. After writing the value select **Apply**.
- To select all the items click at the top left on the table title and then on the **Trash** Icon.
- Once all the operations have been done, **Save** the edits and close the attribute table.

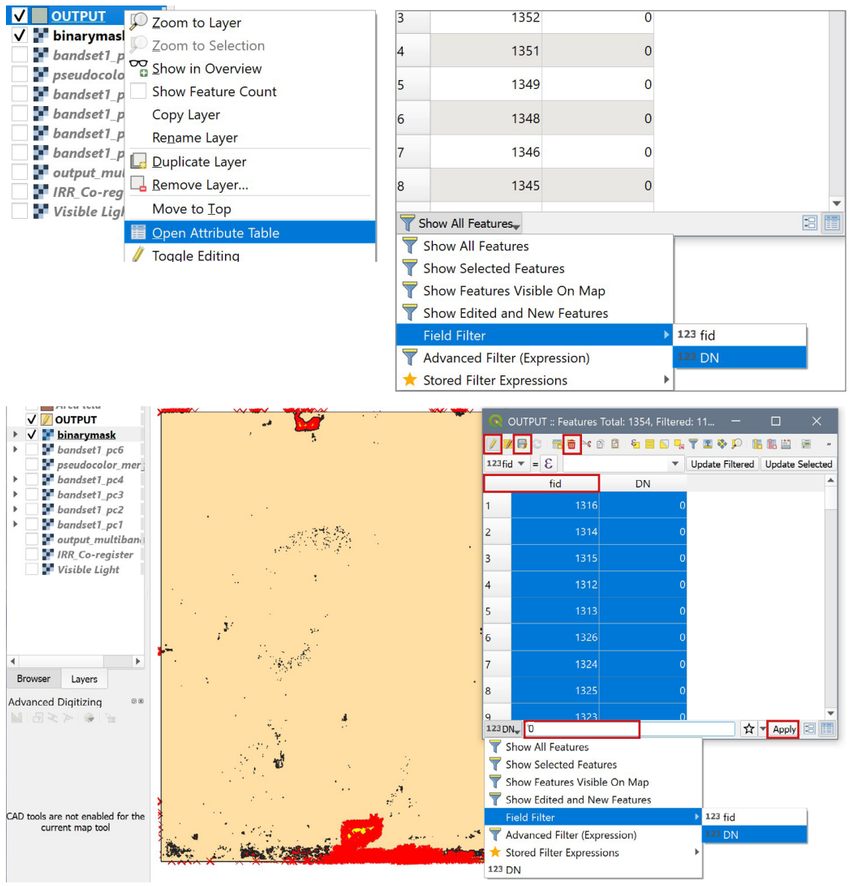



Figure 4.30
Screen Shot of QGIS. Attribute Table



The algorithm produces complex and irregular high dense polygon geometries, with highly jagged edges that exactly follow the ROI boundaries; an example is shown in Fig. The complexity of the polygons is unavoidable as it accurately reflects the phenomena caused by the various types of degradation.



(a) (b)

Figure 4.31
Example of polygons extracted (a)before and (b) after background removal.

## 4.4.2 Checking and corrections of topological errors

Before proceeding to the next operations it is necessary to evaluate and correct possible topological errors caused by this complex conversion.

- In QGIS to perform the error check activate and use the **Geometry Checker Plugin** (Fig. 4.32).
- From the panel click on the **wrench** icon. Select the Layer to be corrected and the type of error to be found. Different errors can be added, for the proposed methodology it is important to find the following errors: **must not have invalid geometries** and **must not overlap**. Click on OK to close the window (Fig. 4.33).
- Then click on the icon to **start the verification**. A list of all errors will be displayed and the polygons will be highlighted in red. By double-clicking on a single error record, the software zooms in on the respective polygon.

It is important to note that polygon geometries frequently don't have any visible errors, such as adjacency or overlap problems. However, errors in nodes or vertices can occur that interfere with subsequent polygon analysis operations. It is therefore necessary to perform automatic error correction.

- To perform the correction, choose **Fix Geometry** from the **Processing toolbox** list. Select the polygon layer to be corrected and click Run. A new error-free

polygon layer will be created automatically (Fig.4.34).

It is essential to specify that the polygons extracted by this method can be read by other commercial software widely used in cultural heritage documentation, such as Autocad and SICAR.

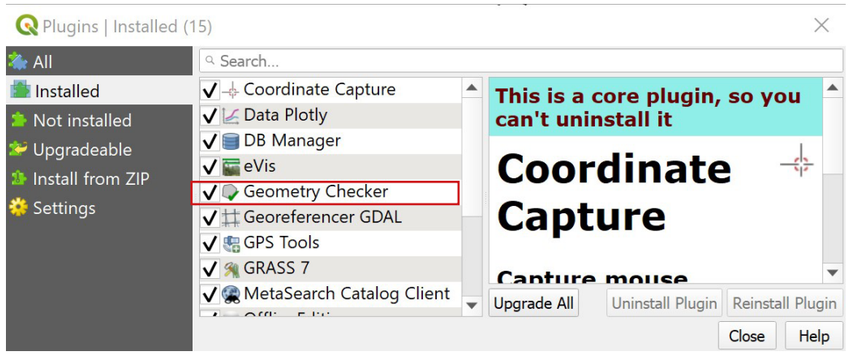



Figure 4.32
Window of Plugins Installed in QGIS. Activation of Geometry Checker Plugin.

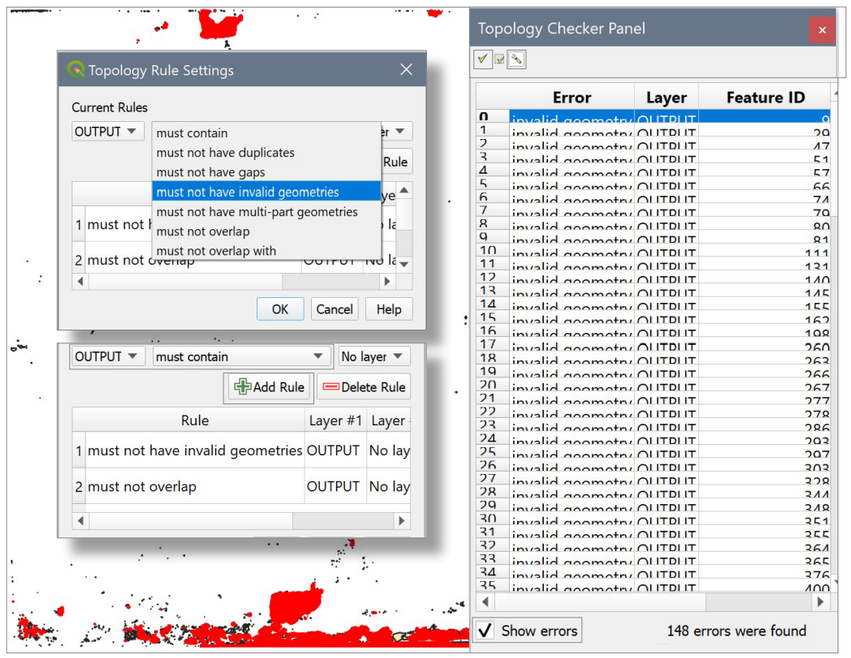



Figure 4.33
Screen Shot of QGIS. Topology Checker Panel of Geometry Checker Plugin.



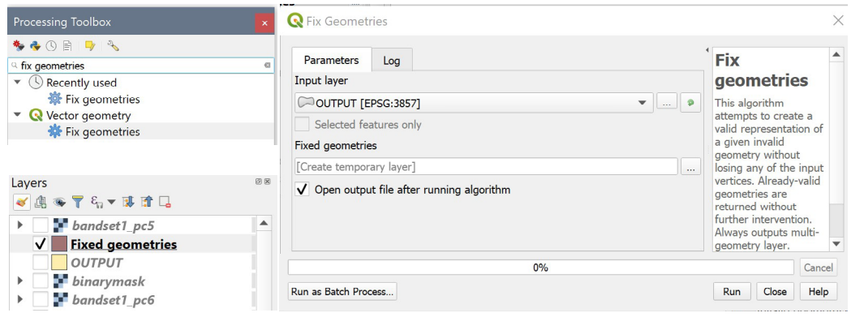



Figure 4.34
Screen Shot of QGIS. Panel of Fix Geometries Tool. and Layer Panel.

Although each extracted polygon is a member of the same layer, it is not connected to the group and represented by a single field in the attribute table (Fig.4.36). This property allows each ROI to be analyzed separately, however to perform some statistical operations it is useful to group all polygons into a single group. It is recommended to perform this operation by preserving both the layer with disjoint polygons and the layer with merged polygons.

- To merge polygons select the item **Vector►Geoprocessing tools►Dissolve** from the menu bar. In the dialog box select the layer and click Run. A new layer will be automatically created with the merged polygons represented by a single field in the **Attribute Table**.

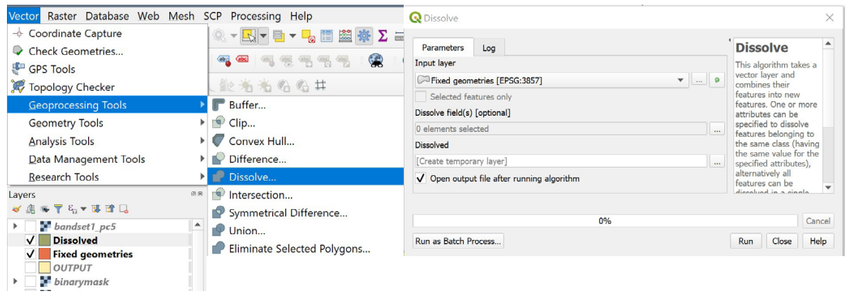
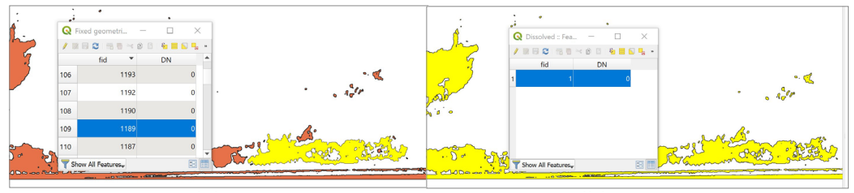



Figure 4.35
Screen Shot of QGIS. Geoprocessing Tools and Dissolve Panel.



(a) (b)

Figure 4.36
Example of polygons extracted and table of attributer of the Layer. (a) Polygon not connected to the group and (b) Polygon after done the merge operation.

# Section 4.5 PHASE II-STAGE V

## 4.5.1 Create a Database

Stage V starts the second phase of the methodology in which the user identifies the polygons following the **Graphic Documentation System** described in section 1.4.1. Each polygon- or group of polygons- is identified in a specific category class or subcategory and is characterized with a specific pattern and color.

As mentioned in the previous section, each layer has an **Attribute Table** in which each row represents a feature, i.e. an image or geometry present on the layer, and each column contains a particular piece of information about that feature, e.g. air, perimeter, etc. Features in the table can be searched, selected, moved, or modified, and characterization and classification operations can be based on these features.

The attribute table is essential for performing mathematical operations on geometries and is related to the export of the legend in the layout phase.

The geometry characterization and attribute table editing operations can all be performed within the **Layer Properties panel**, activated by right-clicking on the specific layer. The items in the panel change depending on the type of layer, i. e. raster or polygonal layer. Below are described some items and basic compilations to perform in the panel.

1. Information : the Information tab is read-only and is a place where is summarized all information referring to that layer.



2. Source : this tab defines general settings for the layer, such as the name and the reference system. The **Layer Name** defines the Layer's classification, e.g. *lacunae, previous interventions, new restoration.*
3. Symbology : the Symbology tab provides several tools to perform polygon characterization. For a single layer there are four types of renderers available:

   - Single Symbol : is used to characterize all polygons on the layer using a single symbol/color or pattern.
   - Categorized : is used to characterize the polygons of a layer based on the discrete values of a field or expression. For example, this type of categorization can be used to classify polygons based on area extent.
   - Graded : similar to the categorization option, it allows the characterization of polygons based on certain discrete values chosen by the user. The color characterization is graduated according to the values.
   - Rule-based : is used to render all the features from a layer, using rule-based symbols whose aspect reflects the assignment of a selected feature's attribute to a class. The rules are based on SQL statements and can be nested. The dialog allows rule grouping by filter or scale, and you can decide if you want to enable symbol levels or use only the first-matched rule

   Symbols and patterns can be created and imported into QGIS. This feature is very important for the proposed methodology as it allows the use of normalized graphical symbolisms, described in section 2.4 and 2.1.

4. Labels : This tool allows to associate a textual information called label for each polygon or group of polygons. The available labeling methods are:

   - No label: : the default value, showing no labels from the layer.
   - Single labels: show labels on the polygon using a single attribute

or an expression

- rule-based labeling: multiple label configurations can be defined and applied selectively on the base of expression filters and scale range, as in Rule-based rendering.
- : allows setting a layer as a visual obstruction for labels on other layers.

Labels are particularly useful for documentation needs. The operator can export non-canonical thematic mapping, or simple images or pdfs of the project, where labels are used as additional information to clarify the meaning of the used symbology.

5. Diagrams : Similar to labels, this tool allows to associate a graphical overlay with each polygon or vector layer. The available graphics are

- No diagrams: the default value with no diagram displayed over the features.
- Pie chart: a circular statistical graphic divided into slices to illustrate numerical proportion. The arc length of each slice is proportional to the quantity it represents;
- Text diagram: a horizontaly divided circle showing statistics values inside;
- Histogram: bars of varying colors for each attribute aligned next to each other;
- Stacks bars of varying colors for each attribute on top of each other vertically or horizontally.

6. Fields : This tool provides information about the fields in the **Attribute table** related to the layer and helps to organize them. In this panel the table can be modified in its structure using the **Enable/Disable** edit mode and the **New Field** and **Delete Field** buttons. You can also rename fields by double-clicking on the name. Also you can associate a comment with a field, this information is recovered and displayed in the **Comment column** and later displayed when hovering the mouse over the field label in a function form.
7. Actions : QGIS provides the ability to perform an action based on the attributes of a feature. This tool can be used to perform any number of actions, such as running a program or switching to a web page or web reporting tool.



8. Rendering : this tool is very useful because allows to simplify polygons and very complex geometries improving rendering times both during the work and visualization phase of the project and when exporting the PDF of the thematic maps.
9. Metadata : The Metadata tab provides several items and options for inserting and editing specific information about a layer. It is possible to use this tab to enter an actual data report. The items are the following:

- the data **Identification**: basic attribution of the dataset (parent, identifier, title, abstract, language…);
- the **Categories** the data belongs to. Alongside the ISO categories, you can add custom ones;
- the **Keywords** to retrieve the data and associated concepts following a standard based vocabulary;
- the **Access** to the dataset (licenses, rights, fees, and constraints);
- the **Extent** of the dataset, either spatial one (CRS, map extent, altitudes) or temporal;
- the **Contact** of the owner(s) of the dataset;
- the **Links** to ancillary resources and related information;
- the **History/Report** of the dataset.
- A summary of the filled information is provided in the **Validation** tab and helps you identify potential issues related to the form.

Metadata are currently saved in the project file. They can also be saved in a .qmd file alongside file based layers or in a local .sqlite database for remote layers (e.g. PostGIS).

10. Legend : The legend properties tab provides advanced settings for the Layers panel and/or the print layout legend. These options include:

- **checkbox text on symbols**: In some cases it can be useful to add extra information to the symbols in the legend. This box allows to add text to a texture or color characterization assigned to a layer. The text is

displayed above the symbol, both in the Layers panel and in the legend of the print layout. This mapping is done by typing each text next to the symbol in the table widget or filling the table using the Set Labels from Expression button. Text appearance is handled through the font and color selector widgets of the Text Format button.

11. Digitizing: the Digitizing tab gives access to options that help to ensure the quality of digitized geometries, such as a geometry and topology Checks. However, it is recommended to perform these checks with the steps described in the previous sections.

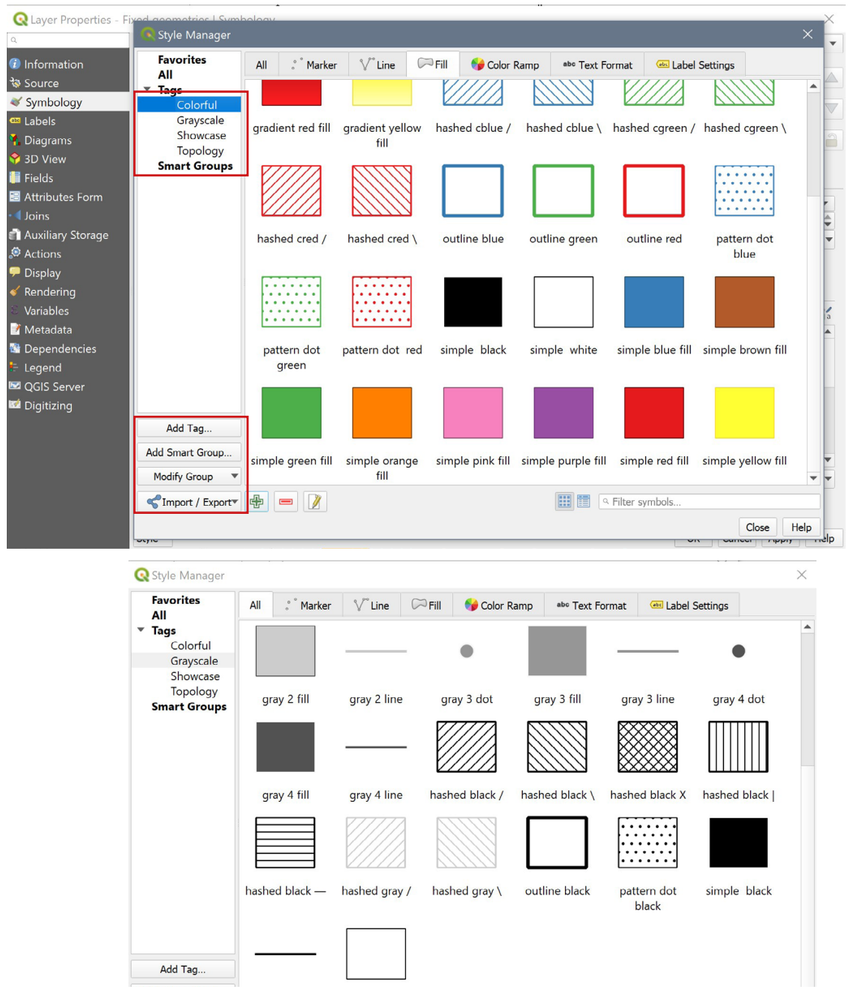



Figure 4.37
Screen Shot of QGIS.
Layer Properties panel of vector layer.
Symbology tool.



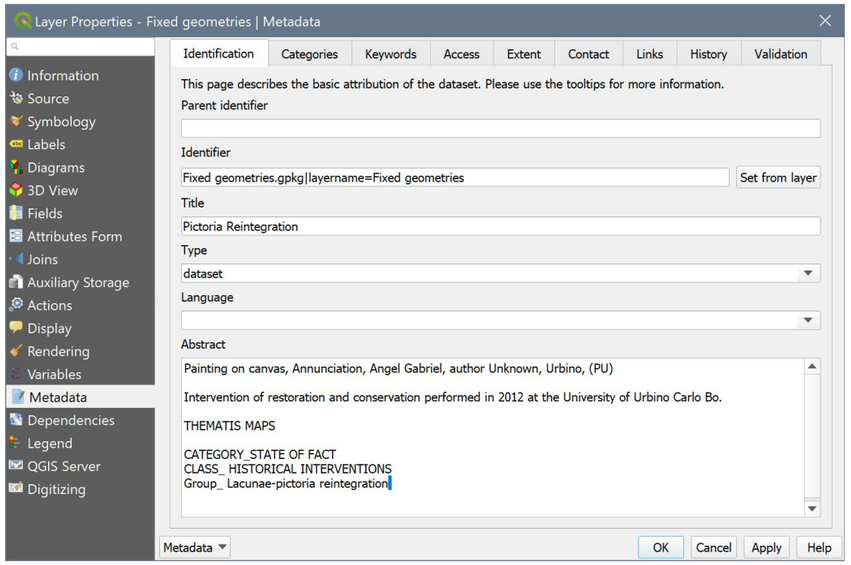



Figure 4.38
Screen Shot of QGIS.
Layer Properties panel.
Metadata tool.

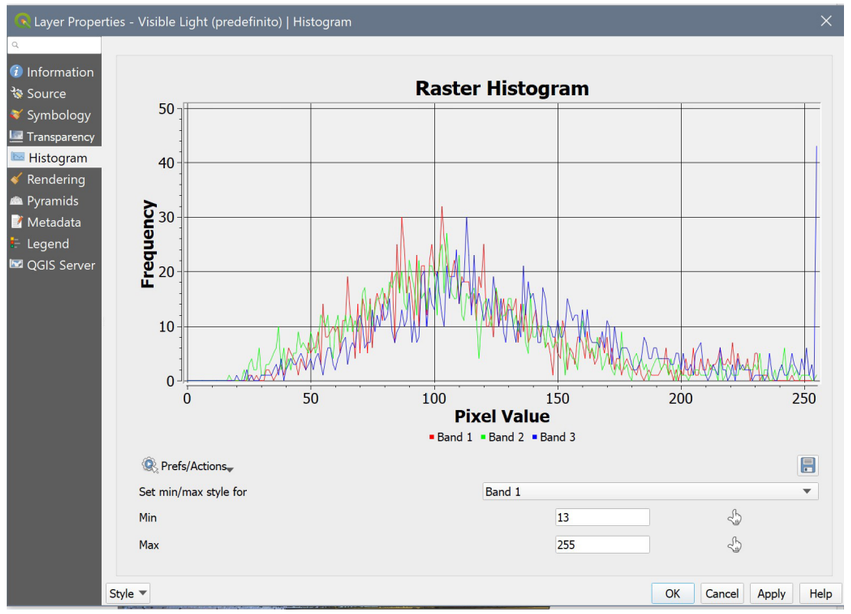



Figure 4.39
Screen Shot of QGIS.
Layer Properties panel of raster layer Histogram tool.

# Section 4.6 PHASE II-STAGE VI

## 4.6.1 Statistical Evaluations

The statistical evaluations depend on the case study, usually the most requested operations in the field of cultural heritage are the calculation of the area and perimeter of polygons or the percentage of occupation of polygons compared to others. Qgis allows to perform several operations, in this section to describe those just mentioned. Since all operations must be performed within the attributes table, in the Table.4.5 are listed and described all the tools in the panel.

***Obtain information about area and perimeter***

Polygons extracted with raster to vector conversion contain only two fields: fid which corresponds to the polygon number and DN which corresponds to its vector value. To perform calculations based on existing attribute values or to calculate new attributes or fields with specific functions, it is necessary to use the **Field Calculator** tool.

- Activate the **Edit Mode** and open the **Field Calculator**.
- In the dialog select whether it is required to update the selected features, create a new attribute field where the calculation results will be added, or update an existing field.
- Select the **Create a New Field** checkbox to save calculations in a new field. When opting to add a new field, it is necessary to attribute some information to the field such as a name, type (integer, real or string), total field width and field precision (Fig. 4.41). For example, if choosing a field width of 10 and a field precision of 3, you will get 6 digits before the dot, then the dot and another 3 digits for the precision.
- Expressions can be searched at the side of the panel (Fig.4.41). To calculate the area write **area ($geometry)** and click ok. A new area field will be automatically loaded for each polygon (Fig.4.40) At this link it is possible to find the complete list of expressions[1].
- To perform the perimeter calculation just write in the expression panel the **$perimeter** operation and click on ok.

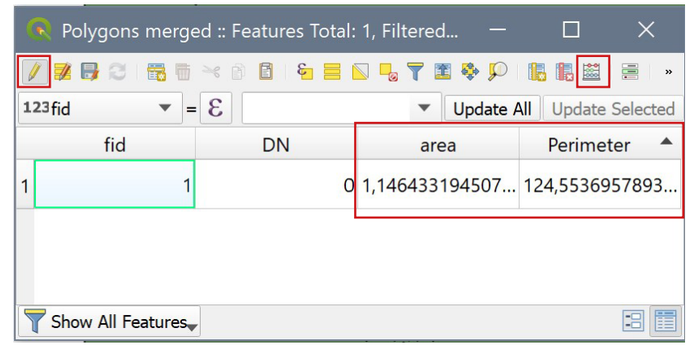



Figure 4.40
Attribute Table of vector polygon merge layer. Examples of area and perimeter fields extracted from the field calculator.

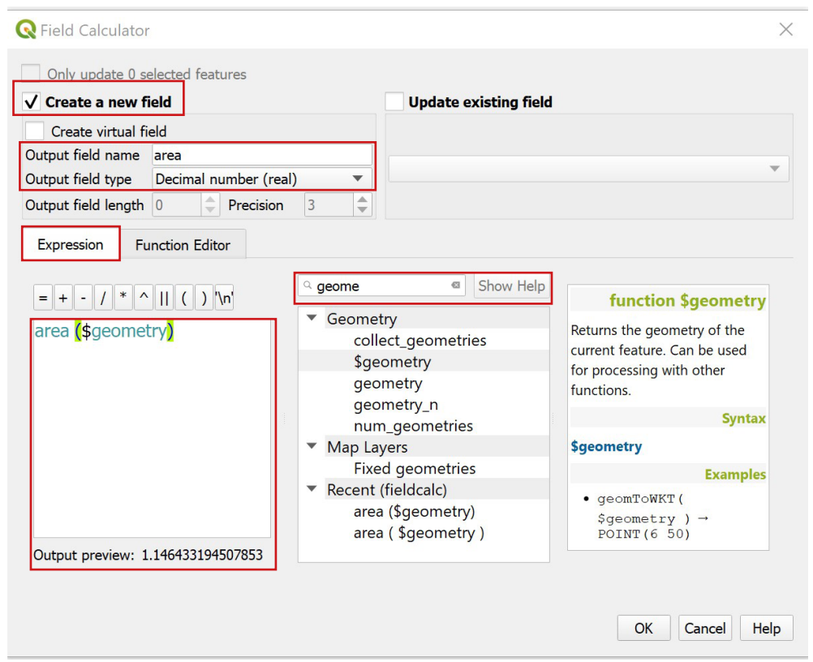



Figure 4.41
Field Calculator Panel. Example of area calculation.

Table 4.5
Description of the actions, Tools and buttons present in the attributes table.

| Icon | Label | Purpose | Default Shortcut |
|---|---|---|---|
| | Toggle editing mode | Enable editing functionalities | Ctrl+E |
| | Toggle multi edit mode | Update multiple fields of many features | |
| | Save Edits | Save current modifications | |
| | Reload the table | | |
| | Add feature | Add new geometryless feature | |
| | Delete selected features | Remove selected features from the layer | |
| | Cut selected features to clipboard | | Ctrl+X |
| | Copy selected features to clipboard | | Ctrl+C |
| | Paste features from clipboard | Insert new features from copied ones | Ctrl+V |
| | Select features using an Expression | | |
| | Select All | Select all features in the layer | Ctrl+A |
| | Invert selection | Invert the current selection in the layer | Ctrl+R |
| | Deselect all | Deselect all features in the current layer | Ctrl+Shift+A |
| | Filter/Select features using form | | Ctrl+F |
| | Move selected to top | Move selected rows to the top of the table | |
| | Pan map to the selected rows | | Ctrl+P |
| | Zoom map to the selected rows | | Ctrl+J |
| | New field | Add a new field to the data source | Ctrl+W |
| | Delete field | Remove a field from the data source | |
| | Open field calculator | Update field for many features in a row | Ctrl+I |
| | Conditional formatting | Enable **table** formatting | |
| | Dock **attribute table** | Allows to dock/undock the **attribute table** | |
| | Actions | Lists the actions related to the layer | |



***Obtain information about percentage***

- To calculate the percentage of the total area of a group of polygons, merge them into one field as shown in section 4.4.2 and calculate the area of the merged polygon.
- Then calculate the total area of the second polygon, in our case the polygon corresponding to the area of the canvas.
- In the attribute table of the merged polygon create a new field called **Percentage%** and write the following in the expression panel

(area ( $geometry ) / attribute( get_feature_by_id('Canvas Area',1), 'area')) * 100

Which corresponds to the following query

*Take the geometry area of this layer, perform a division with the area attribute present in field 1 of the Canvas Area layer and divide by 100* (Fig.4.42).

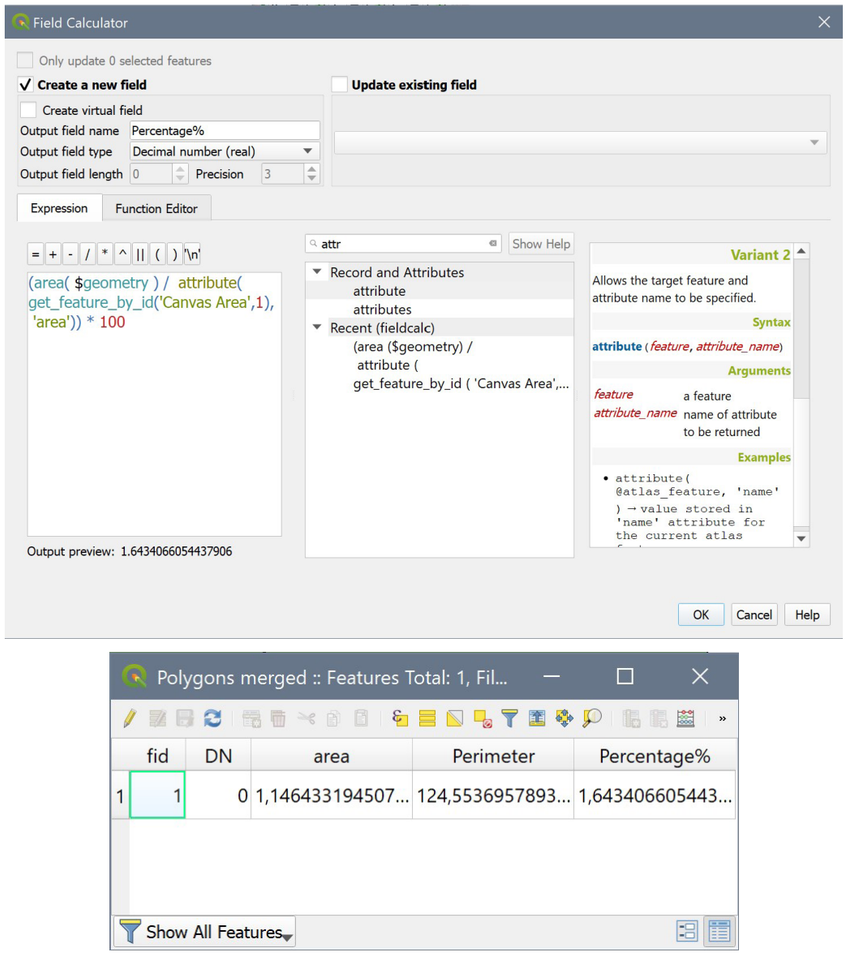



Figure 4.42
Field Calculator Panel. Example of percentage calculation.

# Section 4.7 PHASE II-STAGE VII

## 4.7.1 Layout, printing, storage

Layout is the last stage and consists in the definitive creation of the thematic mapping; this phase is executable only in QGIS. Regarding all the second stage and in general for the goals of the proposed methodology, QGIS has resulted a great tool as it allows to work with graphics as any professional layout and graphics software. From the layout panel it is possible to connect to a device to print the created maps since the thematic maps are currently stored by the competent authorities both digitally and in paper form. However, QGIS allows to perform a number of sharing operations through Web-GIS procedures that could be very useful. For example, these procedures could be used to create an online database similar to SICAR, to allow remote access to the project by other conservators interested in studying the artifact, or for simple scientific divulgation.

The following section summarizes the tools of the **Print Layout** panel.

### 4.7.1.1 Print Layout Panel

Print Layout is a powerful tool that allows to create different thematic maps of the same project. It allows adding all the elements present in the project such as raster images, vector layers, legends, labels, attribute tables and allows adding text boxes, scale bars, basic geometric shapes, arrows, and HTML frames. It also offers all the tools for graphics, for example there are tools to size, group, align, position and rotate each element and adjust its properties to create the layout. The resulting layout can be printed or exported in image, PostScript, PDF or SVG formats. In addition to creating and editing graphics, the panel also allows editing the font type, color and size of the text.

Each executed Layout can be saved as a template and can be loaded in another project session. Finally, the generation of several maps based on a template can be done through the atlas generator. It is important to point out that the hierarchical order in which the Layers are arranged in the Layout panel determines their overlap in the Print Layout. By using the new **Data Plotly Plugin**[1], it is possible to export statistical evaluations in the form of graphs. QGIS also allows to export PDF files with layers in which each object inserted in the layout can be viewed separately from the others.

- To create a new layout and open the panel click on the icon in the menu bar and then name the Thematic Mapping (Fig.4.43).
- To open the Saved Layouts management panel click on the icon in the menu bar.

The panel appears as in the figures 4.46 and presents the toolbar at the top and on the sides. The operations that can be done are really numerous, in this section we will limit just to show in images all the tools available for creation and editing and we will show an example of thematic mapping made with this tool.

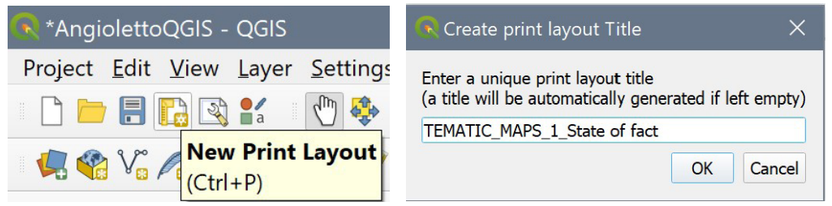



Figure 4.43
Screen shot of the QGIS menu bar. Icon to open the layout panel and dialog box to name the folio where the thematic mapping will be layout.

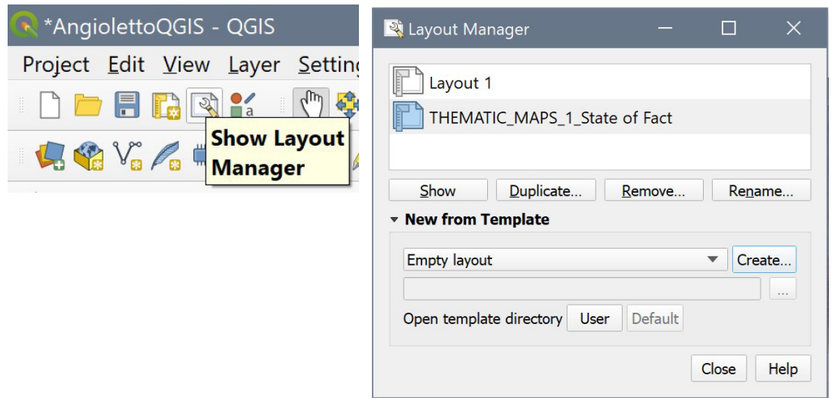
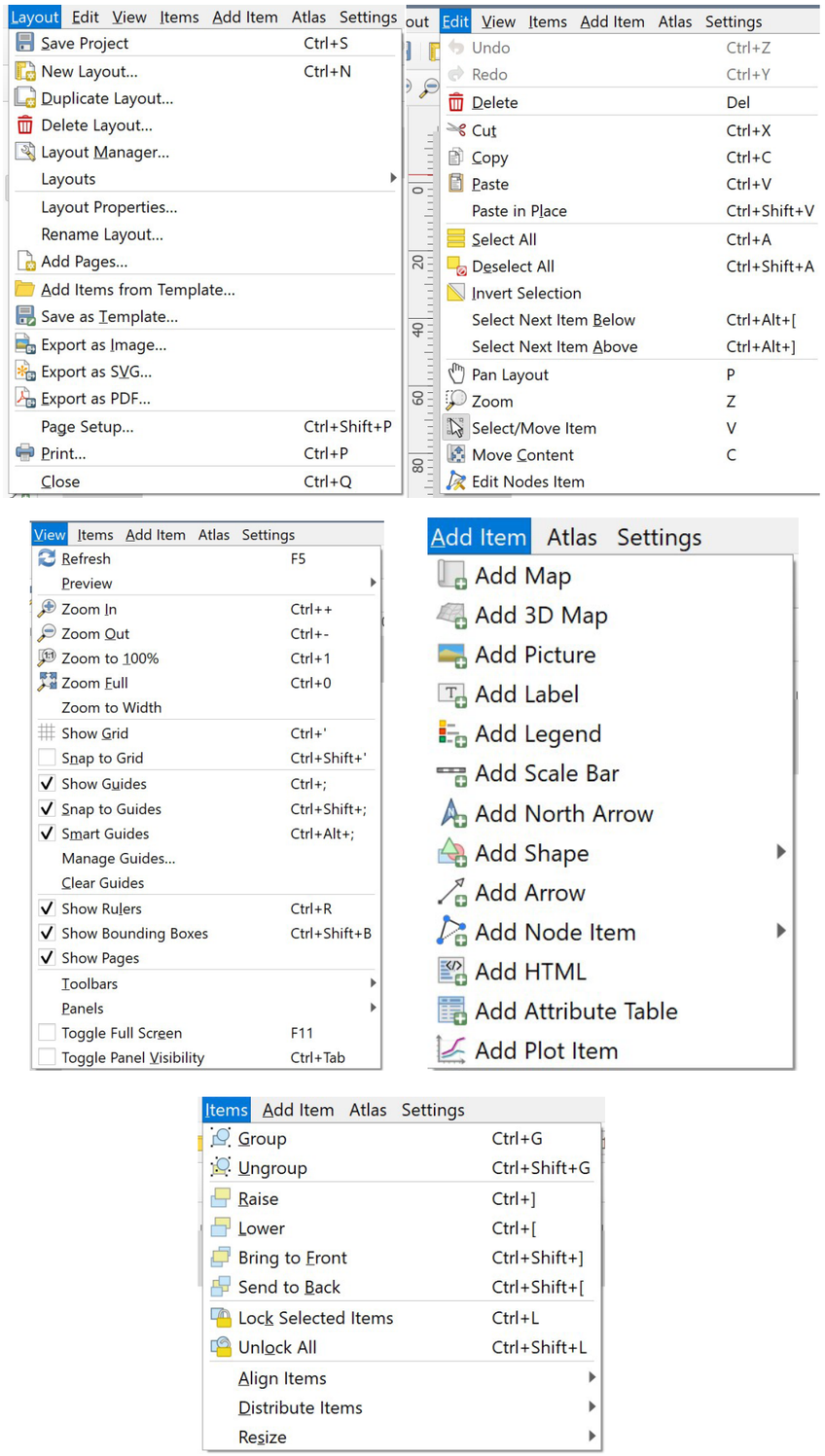



Figure 4.44
Screen shot of the QGIS menu bar. Icon to open the layout Menager, to view and edit layouts saved as templates.

Figure 4.45
List of functions that can be executed in the Layout and Print panel





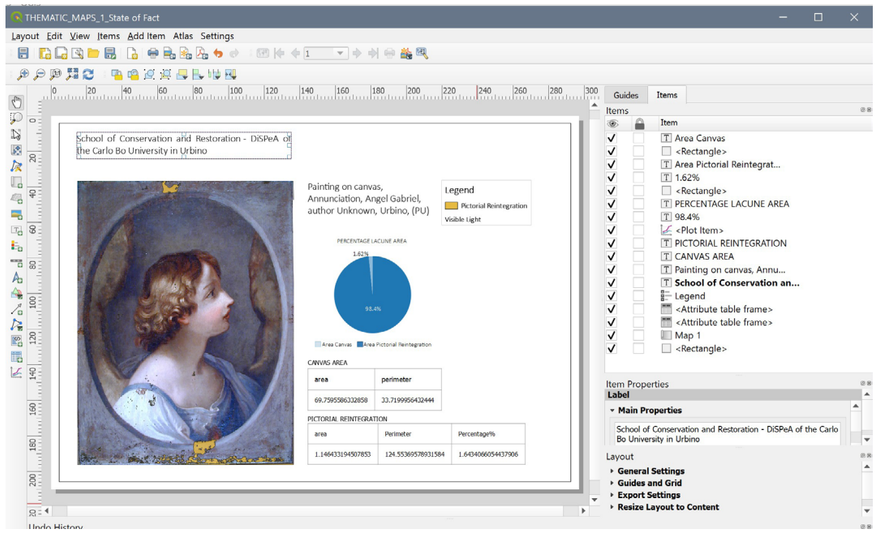




Figure 4.46
Appearance of the QGIS Layout and Printing panel.

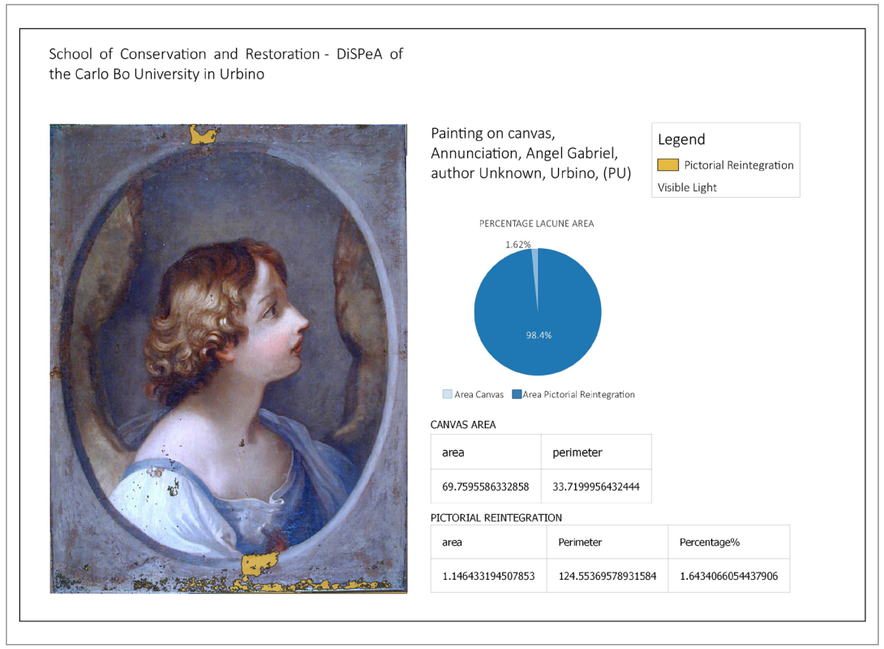



Figure 4.47
Example of a thematic mapping layout in QGIS and exported in PDF format.

# CHAPTER V

# Case Studies

Methodologies described in the previous chapters has been tested on three canvas paintings, characterized by three growing levels of complexity, mainly deriving from their conservation history, executive techniques, and kind of degrade conditions. In particular, the third case complexity allowed us to test different image analysis processes, combining them with statistic percentage analysis and virtual proposals for pictorial reintegration.

# Section 5.1 The "Ecce Homo" by Bernardo Strozzi

This section illustrates diagnostics and documentation carried out on the Ecce Homo, canvas painting by Bernardo Strozzi. This canvas is kept and exhibited in the National Gallery of Palazzo Spinola, in Genova; it recently underwent a conservation and preservation intervention including the cleansing of a surface varnish layer, removal of the old restoration intervention and finally a pictorial retouching whit varnish. This case study was the first one on which methodology was tested, because conservative issues were already known and diagnostic investigations had clearly pointed out Regions of interest (ROI) presenting features connected to the previous interventions.

## 5.1.1 Phase I-Stage I: Image Acquisition

The artifact was photographed in different ways, under visible light effect, with two Nitraphot 500W diffused light projectors and using a Macbeth Color Checker as reference; the RGB color image was captured by a Nikon D800 photo-camera. The Ultraviolet-induced luminescence (UVL) image was taken by a Nikon D800 camera with Hoya IR-UV-cut digital filter, with lighting by two Labino UV lamps and using a 99% bario-sulfate tile and a Macbeth Color Checker as references. From this UVL image visible light was then subtracted, so as to further enhance materials' response to fluorescence. The infrared-reflected (NIR) image (780-980 nm),was then captured by a Nikon D800 Iruv camera with Peca 87c and 87b filters, under the light of two Nitraphot 500W diffused light projectors and with a Macbeth Color Checker reference[83].

| Investigation | Camera | Filter | Irradiation | Reference |
|---|---|---|---|---|
| Visible Light | Nikon D800 | none | Nitraphot 500W 2x | Macbeth Color Checker |
| Ultravio-let-induced lumines-cence (UVL) | Nikon D800 | Hoya IR-UV-cut | lamp Labino UV 2x | Color chart X-RITE<br>Reference 99% Minolta not-fluores-cent; parasite light subtraction |
| Infrared-re-flected (NIR) | Nikon D800 | Peca 87c<br>Peca 87b | Nitraphot 500W 2x | Macbeth Color Checker |

Table 5.1
Modalities and equipment for the acquisition of diagnostic investigations

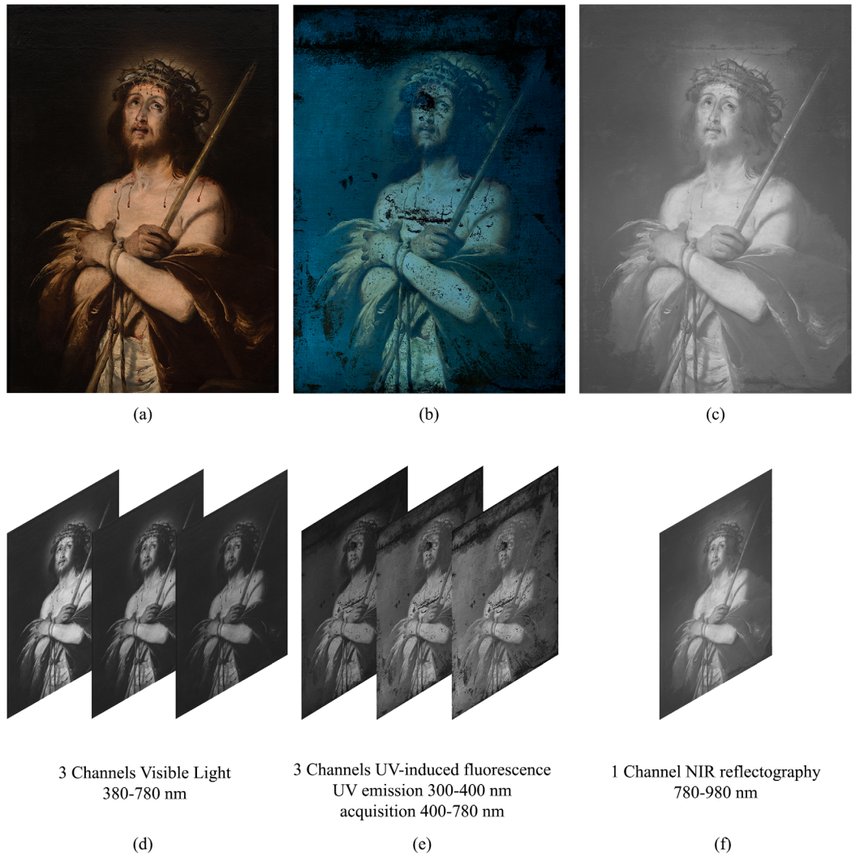



Figure 5.1:
Phase I, Stage I- Ecce Homo by Bernardo Strozzi, oil on canvas, 1620-1622, 105 75 cm.

(a) Standard RGB;
(b) Ultraviolet-induced luminescence (UVL);
(c) Infrared-reflect-ed (NIR) images;
(d)(e)(f) Respective Spectral channels of the acquired images.

Images captured by Paolo Triolo, with permission of the Ministry of Cultural Heritage and Activities and Tourism, National Gallery of Palazzo Spinola, Genoa, Italy.

These images represent the input data group, made of seven spectral channels as shown in figure 5.1(d-f): three channels for visible light imaging, three channels for induced fluorescence and one channel for infrared. Through a visual examination of the different channels and the actual artifact, diagnosticians and restorers recognized and localized visually the relevant regions, dividing them into categories and subcategories, as summarized in table 5.2 [144]. Nevertheless, even though each channel presents overlayed and mixed features, we will show how recognizable categories and subcategories can be obtained and represented graphically in a semi-automatic way, by applying the methodology.

Table 5.2:
Categories and subcategories identified by experts based on the data in Figure 5.1.

| CATEGORIES | SUBCATEGORIES | THEMATIC MAPPING |
|---|---|---|
| Executive Mode | Pictorial Film | Red Lac |
| Previous interventions | Pictorial Film | Pictorial Reintegration background |
| | | Pictorial reintegration with Titanium on the figure |



RED LAC

Visible Light PCA Output



PICTORIAL REINTEGRATION BACKGROUND

UVL PCA Output



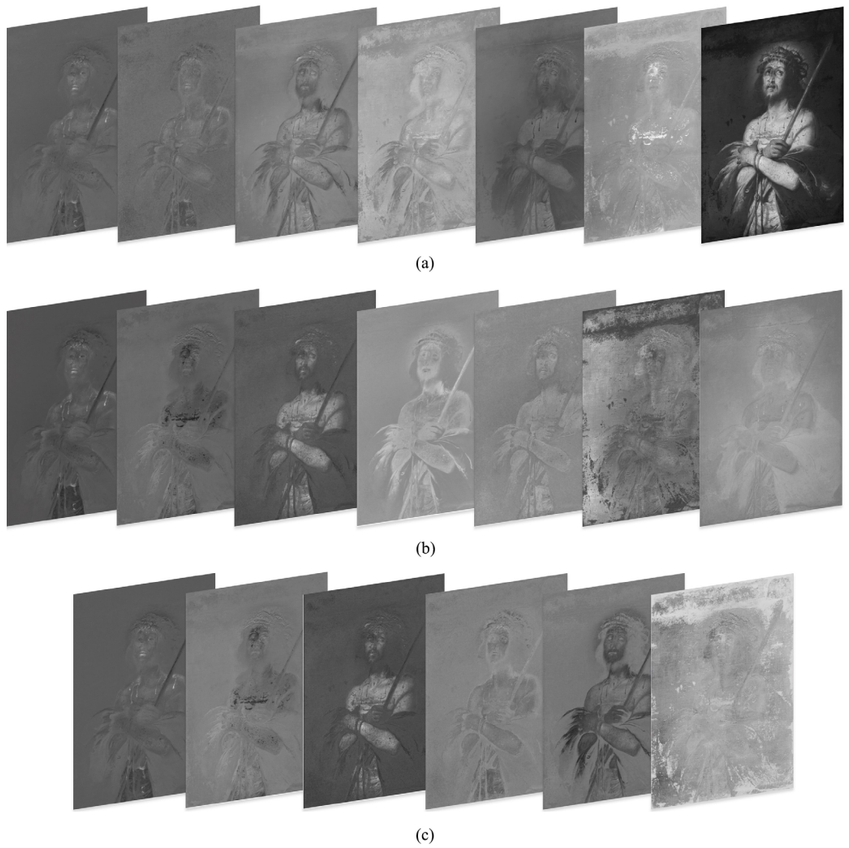
PICTORIAL REINTEGRATION ON FIGURE

UVL PCA Output



## 5.1.2 Phase I-Stage II: Image Analysis trough Blind Source Separation (BSS) algorithms

In the second stage, the seven channels were simultaneously elaborated with PCA and ICA algorithms, see output in figure 5.2(a-b). A further trial with ICA was carried out on a sub-set of 6 channels obtained by excluding the infrared image, see figure 5.1(c), and with consequent image output in figure 5.2(c). These 20 output images are the new data set which conservator/restorers can inspect to study and recognize the features. To apply PCA in phase 2, we used elaboration tools for raster GRASS i.pca analysis available within QGIS© 3.10.2. On the other hand, no ICA tool is available in QGIS© 3.10.2, thus we used an independent Matlab implementation (FastICA)[111].



(a)

(b)

(c)

Figure 5.2:
Phase I, Stage 2:
(a) Output channels obtained by PCA from the entire data set in Fig.5.1;
(b) Output channels obtained by ICA from the entire data set in Fig.5.1;
(c) Output channels obtained by ICA from the multispectral imaging group without IR data in Fig.5.1 (a)(b)(d)(e).

## 5.1.3 Phase I-Stage III: Extraction of binary masks through threshold algorithms

After inspecting output channels, restorers selected only the ones in which regions of interest (ROI) could be seen as well separated from the others.

These channels, belonging to the PCA outputs, are shown in figure 5.3(a)(b)(c) and reveal some features connected to the materials used: in figure 5.3(a) pictorial retouching carried out on the background has been enhanced, whereas in figure 5.3(b) pictorial retouching is on the body of Christ. In the initial data, these two features are visually united in the same spectral channel, while in this phase, they are separated in different channels, even though they were carried out at the same time. Thus, we can affirm that segmentation is caused by the different retouching pigments. The figure of Christ was restored using titanium white pigment, while the background was restored with varnish colors. Even without using destructive chemical analysis or any other more specialized investigation technique, image elaboration has allowed us to distinguish between regions which instead appeared similar through acquired channels. Similarly, in figure 5.3(c) the red lacquer used for Christ's blood has been enhanced.

Only upon these three channels, selected by the restorers, the methodology's third phase was carried out, with the creation of binary masks through threshold algorithms. In our case, in an interval between 0 and 255, we selected T = 180.

For the binarization phase we used QGIS© 3.10.2, in particular the Raster Calculator tool. The result is shown in figure 5.3 (d)(e)(f).



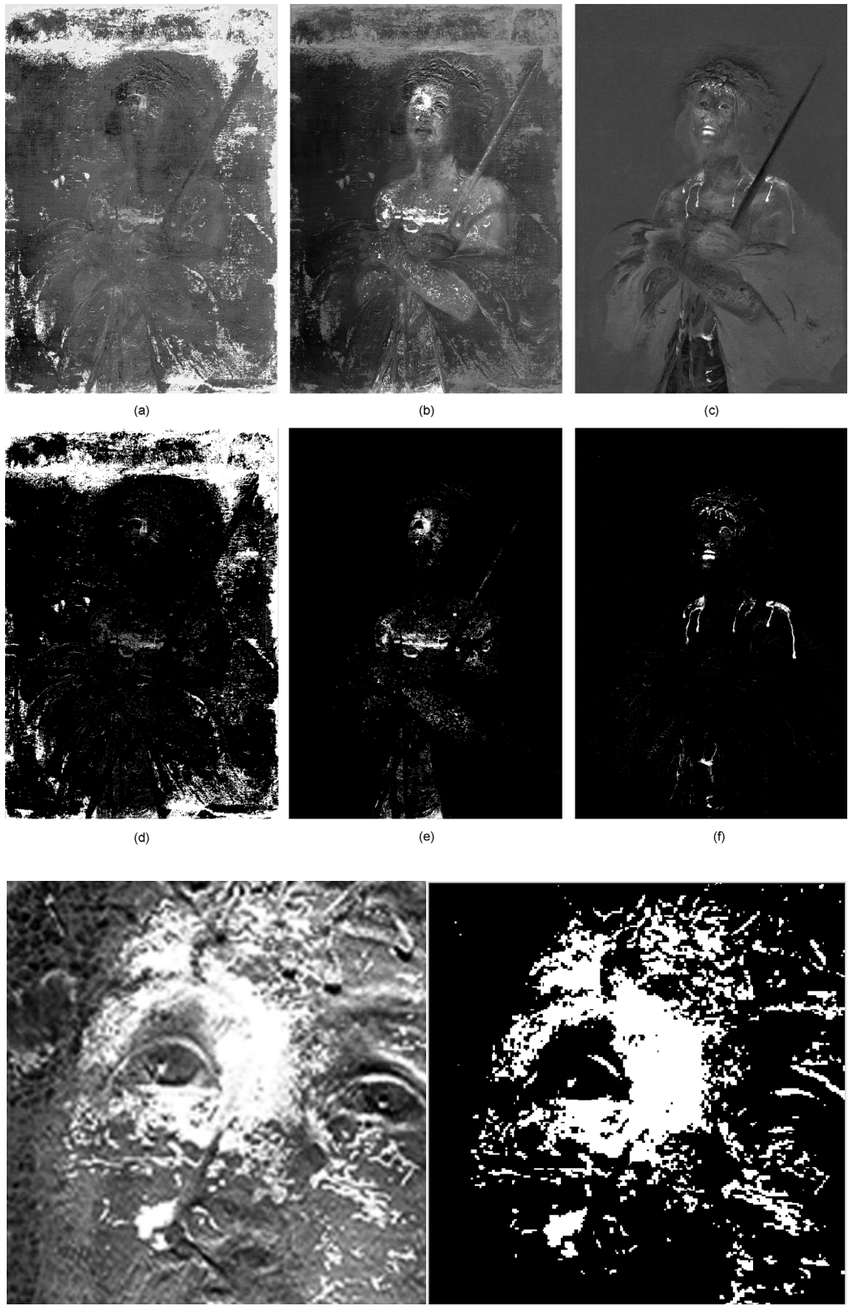



Figure 5.3:
Phase I, Stage III
(a)(b)(c) Images processed from the previous stage (in Fig. 5.2) and chosen to identify the ROI;
(d)(e)(f) Corresponding binary versions.

## 5.1.4 Phase I-Stage IV: Conversion from raster to vector

The fourth stage of methodology consists in automatic extraction of the graphic design to create the thematic maps. Binary masks shown in figure 5.4 (a)(b)(c) have been transformed from raster images to vectorial drawings, thus obtaining automatically closed vector polygons which respect topographic norms of vicinity and overlaying. In QGIS, polygonization can be quickly carried out through the raster to vector polygonizer tool. For each new binary mask, the algorithm creates a new layer, enclosing all the polygons present within the mask. This process allows to carry out features' classification in the attributes table, in a correct and organized way. We must point out that this phase should be carried out exclusively on the extracted binary masks. The algorithm supports all kinds of images and also allows to choose between specific spectral bands. However, as described in section 3.2.2-3, an automatic extraction from raster to vector of non-optimized or binarized color or grayscale images does not guarantee the desired results.

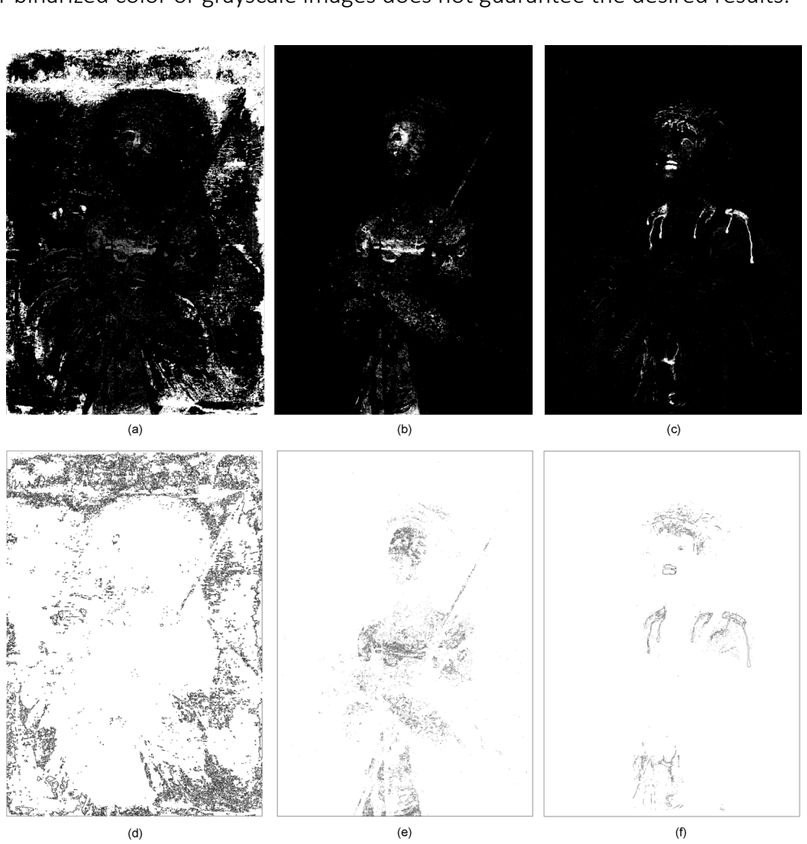



Figure 5.4:
Stage IV: (a)(e)(i) Binary Images (d)(e)(f) and corresponding Image polygonization, conversion from raster to vector.



## 5.1.5 Phase II - Stage V: Database creation

After carrying out image analysis aimed at polygons extraction, the second phase of methodology starts, divided into three main stages including various operations, some of them necessary and others to be assessed, depending on case studies and documentation needs.

Stage V is essential in all case studies, as it represents the database creation. Each polygon extracted and registered in the appropriate class level, is associated to alphanumeric data within the attributes table and characterized (or thematized) by specific colors and textures (see Fig.5.5), using characterization tools available in the Layers style window.

## 5.1.6 Phase II - Stage VI-VII- Statistical Evaluation, Layout and Storage

In this particular case study, no specific statistic assessment was necessary as the canvas was in excellent preservation conditions, thus stage VI in this case was not carried out.

The phase corresponding to stage VII was approached directly, consisting in the creation of a printing layout for the final thematic map. Characterization through the attributes table allowed to automatically export the map key during the print layout phase, including all metadata concerning the polygons in the layout, together with the institution's logo, author's name, the object's dimensions, thematic map serial number, date, documentation executor and a key/legend (or glossary) connected to the vector drawing (see Fig. 5.5-8)

## 5.1.7 Conclusions and publications

This case study was presented in an oral address at the State of the Art (Lo stato dell'arte) 17 Conference, organized by Gruppo Italiano, International Institute for Conservation (IGIIC), and was published in the Conference proceedings [145].

Figure 5.5
Each polygon extracted is characterized (or thematized) by specific colors and textures

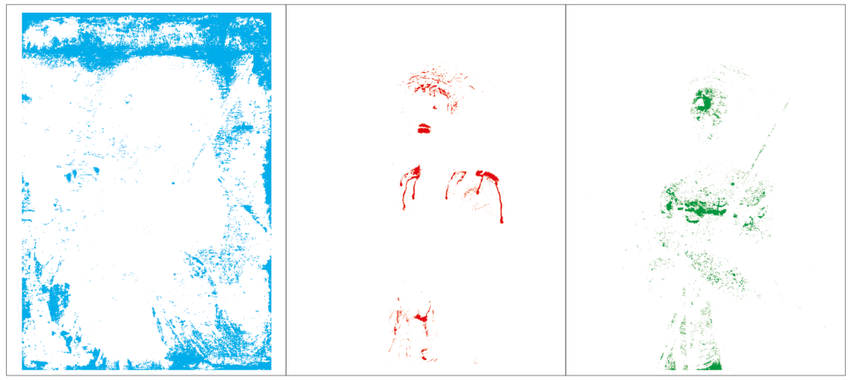


Figure 5.6
Distinction between (a)diagnostic image, (b)object model, (c) information model.

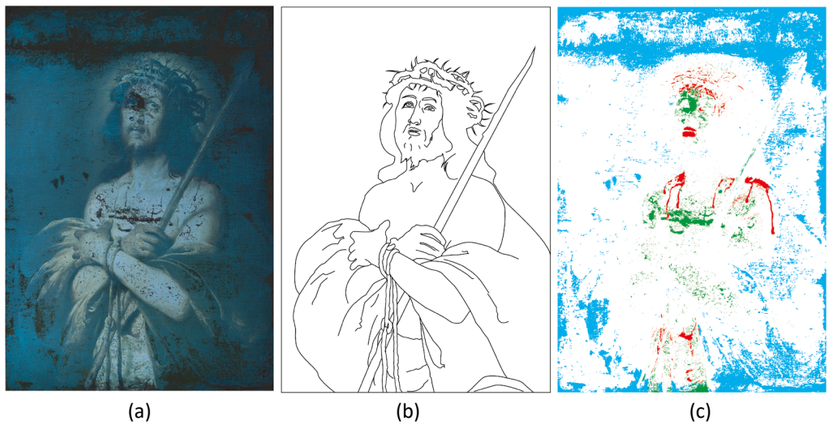



Figure 5.7
Example of thematic mapping using photo instead of object model.





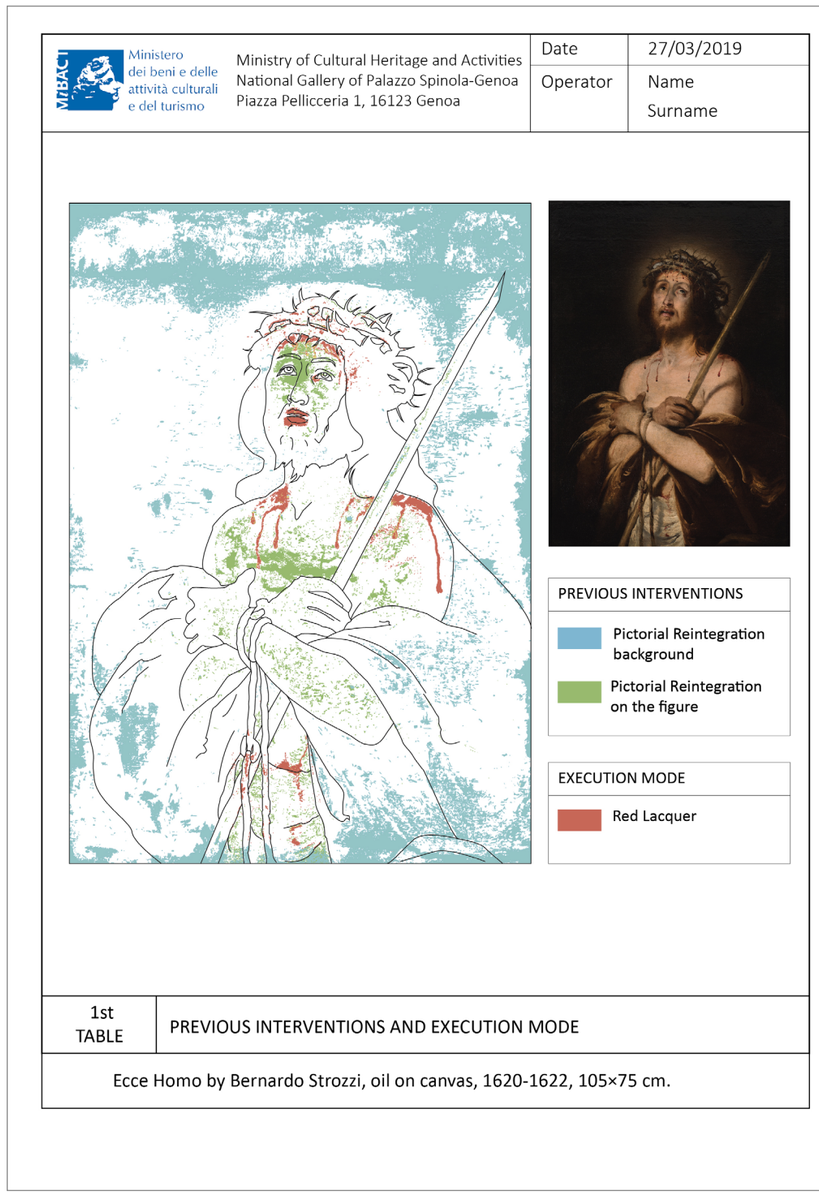




Figure 5.8
Example of complete thematic mapping performed using the object model instead of a photo.

## Section 5.2 "Cleopatra" by Donato Creti

This section illustrates a multidisciplinary study carried out on a canvas depicting Queen Cleopatra, attributed to Donato Creti (Fig. 5.9 a). This painting was donated to a private family by Pope Lion XII on 27 August 1827.

The painting was in poor preservation conditions; it had undergone various unorthodox restoration interventions during the years: the canvas had been lined, cleaned with chemicals and heavily retouched. On the painting's surface there were numerous blisters and liftings[1] and flaking of paint film layer[2], especially in the lower part, possibly due to significant thermo-hygrometric variations. There were dirt deposits on the surface, and the surface varnish was strongly aged[3].

During the latest restoration intervention, carried out in 2019, restorers identified some inpainting and retouching[4] carried out after the author's death by unknown artists or restorers.

We also know that Donato Creti was in the habit of repainting his subjects; Giampietro Zanotti, painter and art historian of his time, wrote that: "for his profession, he is always studying, sighing, is made anxious by his desire for perfection and glory, and never tires of finishing and refinishing his work" [146].

In 2019, during a superficial canvas cleaning, restorers singled out some pentimenti 5 carried out by the artist on the profile of Cleopatra's face, the eye and the hands (Fig.5.9 f, d). Furthermore, on the canvas there were various traces of fillings left by previous restorers( Fig.5.9 b), and also some repainting, particularly visible in the area of the neck and on the shoulder (Fig.5.9 e).

In this case study, regions of interest (ROI) to be divided and documented in the graphic cards can be classified into three categories: artist's pentimenti, old restoration work, conservation and preservation work carried out in 2019. Our aim is to highlight and separate the various regions through image analysis and automatic extraction of vectorial areas.




Figure 5.9:
(a) Cleopatra by Donato Creti (Cremona 1671, Bologna 1749), oil on canvas, 100 77 cm. RGB standard; after conservation work,
(b) image captured during conservation work. Gaps filled in 2019 (to replace missing areas of loss);
(c) Removal of old varnish Aging;
(e) Old gaps filled from previous restorations works and repainting not performed by the original artist.
(f) (d) Pentimenti of the artist visible in the profile of the nose and neck and in the fingers of the hands.

1 *Blister:* disruption causing an area to protrude from the painting's surface; separation of the paint from the ground, or both layers from the support. *Lifting:* the rising of the paintings surface; layer separation.

2 *Flaking*: extreme cracking causing paint and/or ground layer to dislodge from the support, often through a combination of cleavage and cracking.

3 *Varnish Aging*: natural resin varnishes turn first golden in hue and then progressively darker with age, causing a serious distortion of the artist's original colors.

4 *Inpainting and Retouching*: a restoration process to cosmetically re-establish color and/or detail to losses in the paint layer; generally accomplished with pigment in an appropriate binding medium applied by brush. Also called retouching.

5 A *pentimento* (plural *pentimenti*), in painting, is "the presence or emergence of earlier images, forms, or strokes that have been changed and painted over". The word is Italian for 'repentance', from the verb *pentirsi*, meaning 'to repent'.

## 5.2.1 Phase I-Stage I: Image acquisition

The input image dataset was captured in different modalities: under visible light illumination, with two Nitraphot 500W diffuse-light projectors and a Macbeth Color Checker used as reference, an RGB image was captured by a Nikon D800 camera. An infrared image (IR) at 1050 nm (Fig.5.10), with a high dynamic range (16 bits), has been acquired through a multispectral system based on Morovian G2-8300 (CCD KAF 8300 18.1 × 13.7 mm pixels 5,4 × 5,4 µm). The sensor is cooled to reduce the electronic noise during acquisition. The spectral resolution is obtained through interferential filters with ± 25 nm passbands around the central wavelengths 450, 500, 550, 600 and 650 nm in the visible range and 850, 950 and 1050 nm in the near infrared. This choice ensures a complete and continuous coverage of the visible range plus three infrared channels.

Actually, in the three near infrared images we can appreciate the clothes pleat lines as drawn by the author and all the old gaps filled in previous restorations works[6]. In particular, in the image acquired through the 1050 nm wavelength, all the artist's pentimenti recognized during restoration are evident and new pentimenti have been discovered in the hairdo and in the dress.

Table 5.3:
Modalities and equipment for the acquisition of diagnostic investigations

| Investigation | Camera | Filter | Irradiation | Reference |
|---|---|---|---|---|
| Visible Light | Nikon D800 | none | Nitraphot 500W 2x | Macbeth Color Checker |
| Infrared-reflected (IRR) | Morovian G2-8300 (CCD KAF 8300 18.1 13,7 mm pixel 5,4 5,4 µm) | interferential filters with ± 25 nm passbands 450, 500, 550, 600 e 650 850, 950, 1050 nm | Nitraphot 500W 2x | Macbeth Color Checker |



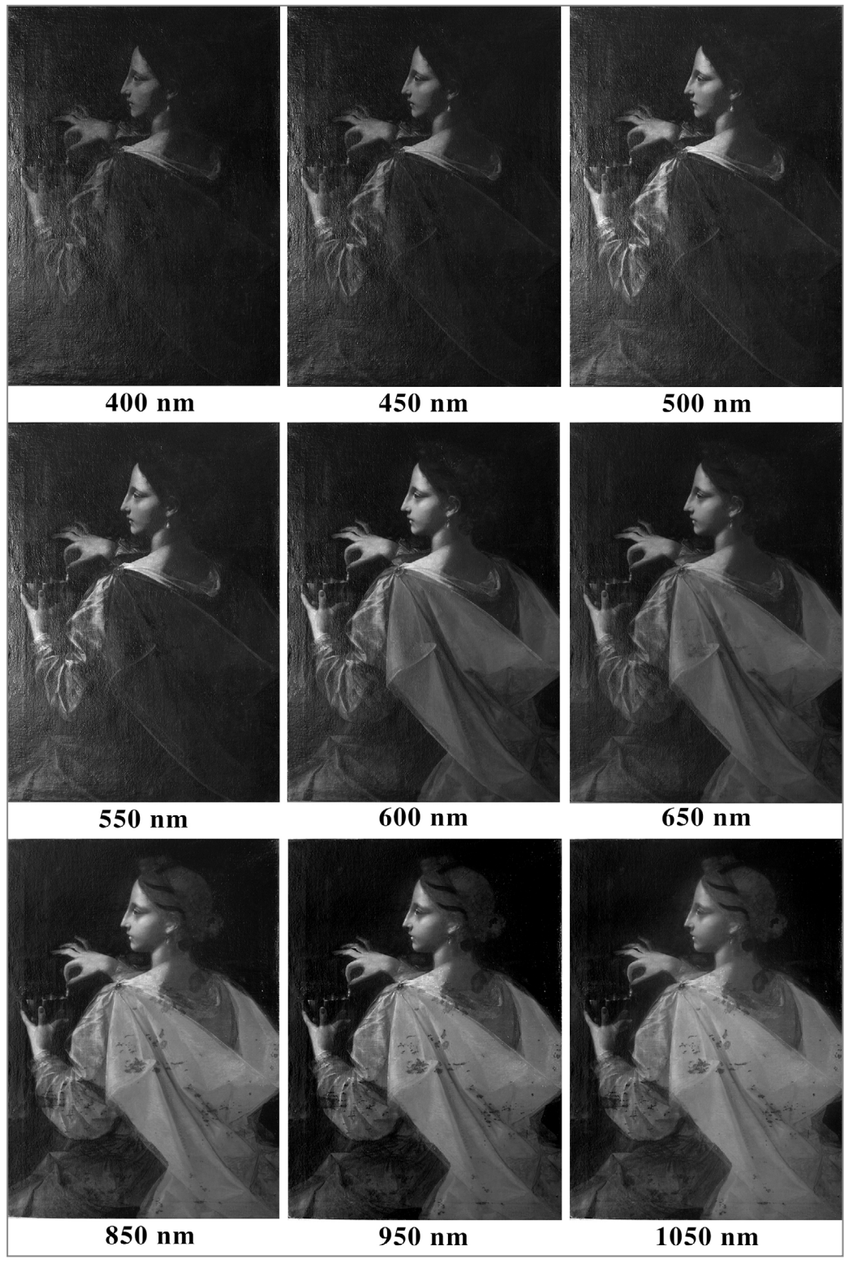



Figure 5.10:
Cleopatra of Donato Creti. The complete set of multispectral acquisitions performed by Vincenzo Palleschi.

### 5.2.1.1 Analysis whit X-ray fluorescence spectroscopy (XRF)

In addition, to correctly date pictorial retouching interventions, the painting was analyzed with the X-ray fluorescence spectroscopy (XRF) technique, which allows to estimate elementary composition of the paint film without taking a sample. The tool used for this analysis is the XRF energy dispersion spectrometer produced by Xglab (Milan, Italy); a tube energy of 40 kV, with a current of 60 µa (3.2 W) and a capture time of one minute per sample. The X-ray tube has a rhodium anode. The spectrometer uses a large Silicon Drift X-ray detector (25mm2) with an energy resolution of 130 EV at 6 Kev.

In painting analysis, X ray fluorescence (XRF) [147], generally combined with multispectral acquisitions, is a standard analysis used to investigate the elementary chemical nature of applied pigments, which appear similar to the eye but differ in their chemical composition. In the case of paintings, analysis is purely qualitative, meaning it simply indicates presence of one chemical element rather than another. Using information coming from the XRF survey and the imaging and comparing data with a summary on the use of pigments in history of art, we can assess if the pigment hypothetically detected in the surveys is consistent with the original artifact dating, or is later.

From XRF analysis and the information learnt from restorers during works, we know that three different mixtures of white have been used on the painting, and retouching was carried out in three different historical moments. The first moment refers to pentimenti by the artist himself, located mainly on the hands, the profile and the hairdo. The second moment can be dated to 1782 when, after the artist's death, the painting was taken into the Vatican's custody and a first restoration and pictorial reintegration was carried out; these are located on the sleeve, the dress and part of clothing under the red cloak. Such hypothesis was confirmed by the presence of the chemical element of Zinc, found by IXRF investigation on those parts. The third moment refers to 2019 conservation work, during which the conservator/restorer removed the aged surface varnish and pigment attributed to the first inpainting and pictorial retouching work. Following this, she replaced areas of loss (Lacune) with new materials. This third moment is spread throughout the artifact and is characterized by fillings, paint strokes, and veiling with varnish colors.



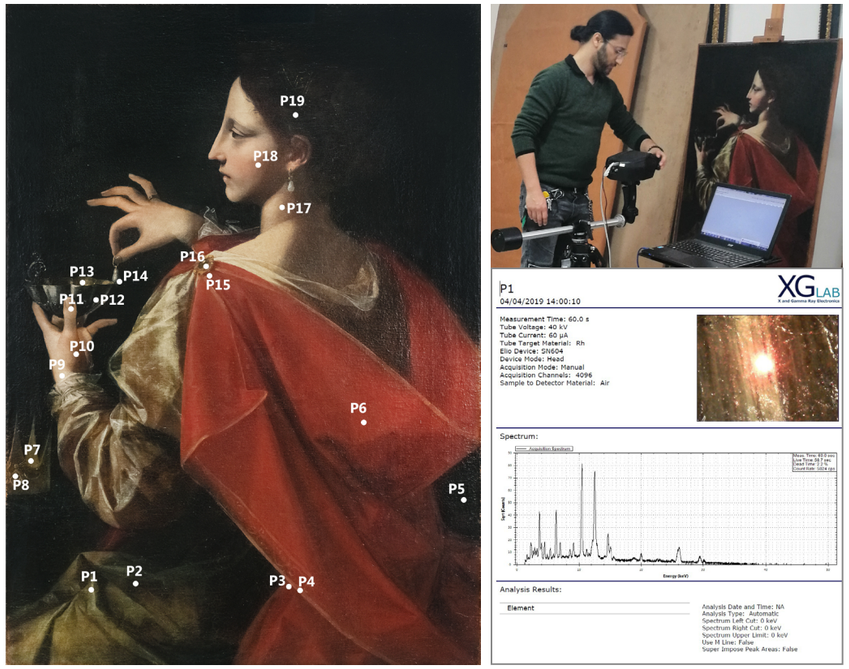



Figure 5.11:
Points analyzed. Identification of measuring points with the XRF instrument. Performed by Stefano Pagnotta.

| Point | Colour | Specific Chemical Elements |
|---|---|---|
| P1 | White/green | **Pb**, Fe, Ca, S, **Ti**, Sb, Cr, Mn, **Zn** |
| P2 | Green | **Pb**, Fe, Ca, S, Mn, **Ti**, |
| P3 | Red | **Hg**, Pb, Fe, Mn, S, Ca |
| P4 | Orange | **Hg**, Pb, Fe, Mn, S, Ca |
| P5 | Cloak | Pb, **Fe**, Mn, S, Ca, Hg |
| P6 | Red | **Hg**, Pb, Fe, Mn, S, Ca |
| P7 | Yellow | Pb, **Fe**, Mn, Ca, S, |
| P8 | Red | Pb, **Fe**, Mn, Ca, S, |
| P9 | White/pink | **Pb**, Ca, S, **Ti**, Fe, Mn, Hg (tr.) |
| P10 | Rose | **Pb**, Fe, Mn, Ca, S, **Ti** |
| P11 | Dark pink | **Pb**, Fe, Mn, Ca, S, **Ti**, Cr |
| P12 | Grey | **Pb**, Fe, Mn, Ca, S, **Ti** (tr.) |
| P13 | Yellow | **Pb**, Fe, Mn, Ca, S, **Ti** (tr.) |
| P14 | White | **Pb**, Ca, S, **Ti**, Fe, Mn. |
| P15 | Red/Yellow | **Pb**, Mn, Fe, Ca, S, |
| P16 | Green | **Pb**, Fe, S, Mn, Ca, **Ti** |
| P17 | White/pink | **Pb**, Ca, S, **Ti**, Fe, Mn, Hg (tr.) |
| P18 | Rose | **Pb**, Ca, S, **Ti**, Fe, Mn, **Zn**, Hg (tr.) |
| P19 | Bruno | Pb, **Fe**, Mn, S, Ca, Hg |

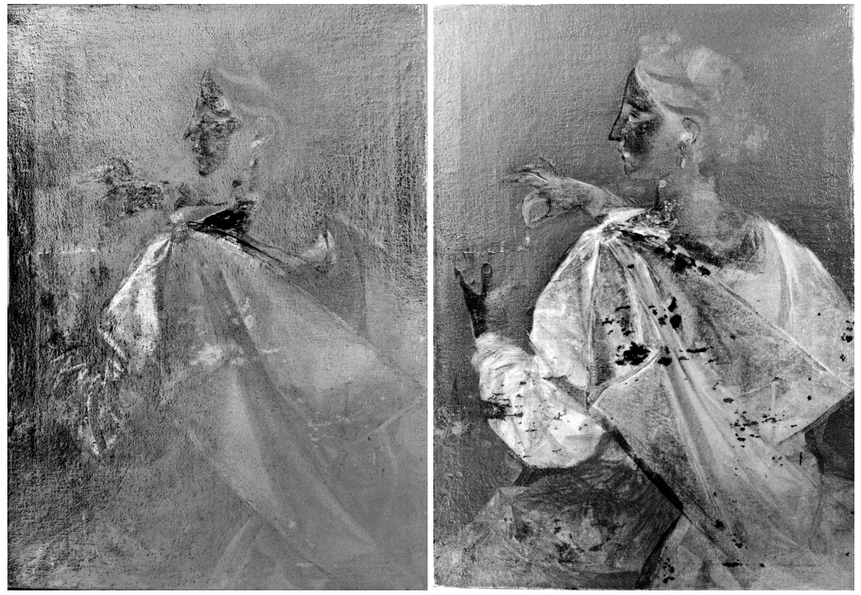
Table 5.4:
Identification of the elements present in the analyzed points (XRF analysis). In bold and underlined the element presenting intensity level peak. This is a purely qualitative analysis.

## 5.2.2 Phase I-Stage II: Image Analysis trough Blind Source Separation (BSS) algorithms

Having assumed the nine channels in figure 5.10 as our input data, we can apply the three BSS elaboration strategies (ICA, PCA) thus obtaining 27 output images, from which we can try to identify the three different moments relating to the painter's pentimenti, to the old restoration work and to 2019 conservation and preservation work. Figure 5.10 indicates the three chosen output channels, all coming from application of the FastICA algorithm, from which the three regions of interest concerning the three different moments can be easily recognized by restorers and extracted through threshold algorithms. In FastICA channel 4, (Fig.5.12 a), the darker regions correspond to pictorial retouching carried out in 2019, especially in the face and shoulder. In channel 3 (Fig.5.12 b), darker regions instead correspond to the old inpainting. These regions are particularly visible on the profile of the forehead, nose, neck, and of the hand and the red tunic. Also the many lacune (missing areas of loss) correspond to particularly dark pixels; actually in this channel we have found two different classes of features. Channel 4 (Fig.5.12 c) holds a lot of information on the various restoration interventions; gray levels represent color thickness, black representing a layer of dense color, whereas pale gray levels represent thinner layers of color. Channel 2 highlights the first original profile of the neck and nose made by the painter.

Complexity of the canvas' preservation conditions has not allowed a perfect subdivision of the three moments, in fact we find output channels including groups of features belonging both to the first and second restoration. In these cases, after automatic extraction of vectorial polygons, a manual reclassification stage made by the operators will be necessary.





(a) (b)

(c) (d)

Figure 5.12:
Some output channels of FastICA algorithm from multispectral set input.
(a) Channel 1
(b) Channel 3
(c) Channel 4
(d) Channel 2

## 5.2.3 Phase I- Stage III: Extraction of binary masks through threshold algorithms

To try and improve extraction of features, in this Stage, beyond the usual threshold algorithm application, also a Neural Network SOM was applied to multispectral images without treatment, with consequent automatic extraction of the binary masks.

### 5.2.3.1 Neural Network SOM Application

Neural network SOM was applied within the Matlab software in two different moments. In the first instance, all acquired multispectral images were elaborated without any treatment, while separately the group of channels in output from algorithms ICA and PCA was elaborated. Outputs did not convey the result hoped for, with the exception of two binary masks in output, in which two Cleopatra profiles were segmented, one related to the artist's first version (Fig. 5.13 a) and the other related to the current state of the artifact (Fig. 5.13 b). Specifically, these two masks are outputs from PCA and they define details connected to the original figure's outline and to repainting, especially on the face and nose. Even through SOM application, many characteristics appeared to be grouped in one mask; the ones presenting significant separation are shown in figure 5.14 a-b and they categorize the various restoration interventions and different kinds of white pigment blends.



(a) (b)

Figure 5.13:
Some SOM outputs with FastICA and PCA input.
(a) current state of the artifact.
(b) The artist's first version of Cleopatra profile.





Figure 5.14:
Some SOM outputs with FastICA and PCA input. Many characteristics, releted to various restoration interventions and different kinds of white pigment blends, appeared to be grouped in one mask.

### 5.2.3.2. Definition of the thematic maps to be obtained

After having visually analyzed all elaboration outputs, restorers chose the ones in which the features relating to the different artifact moments appeared more strongly separated. Given the great quantity of features to indicate, restorers chose to carry out five separate thematic maps to allow data to be properly readable[7].

1. ***Model of the object to describe the first version of the work:***
To carry out this model, a 1050 nm image (Fig.5.16 b) and two SOM outputs from PCA input (Fig. 5.13 b) where chosen.
2. ***Model of the object to describe current state of the work:***
To carry out this model, the RGB image of concluded restoration (Fig.9 a) whose chosen.
3. ***Overlapping of object models 1 and 2.*** (Fig.16 c)
4. ***Model of information referred to previous interventions***
this was created using channel 3 of ICA outputs (Fig.5.12 b)
5. ***Model of information referred to restoration intervention of 2019***
this was created using channel 4 of ICA outputs (Fig.5.12 c).

### 5.2.3.3. Binarization of the chosen images

Each chosen image was elaborated individually with different threshold values, thus obtaining various binary masks.

Only upon these three channels, selected by the restorers, the methodology's third phase was carried out, with the creation of binary masks through threshold algorithms. In our case, in an interval between 0 and 255, we selected T = 180.

To carry out the thresholding we used Matlab, in particular the Image Segmenter App. A morphologic filtering algorithm was applied to extracted binary images, to reduce the noise created by undesired pixels and keep the areas of interest's edges smooth. Transition from gray scale images to binary masks is shown in figure 5.15.

## 5.2.4 Phase I-Stage IV: Conversion from raster to vector

Automatic extraction of the graphic design through polygonization was carried out in QGIS. The chosen binary masks (Fig.5.15) were transformed from raster images to vectorial polygons through the raster to vector polygonizer tool. The algorithm creates a new layer for each binary mask, but in our case the mask extracted from Channel 3 ICA includes two types of features which need to be separated. Concerning the two object models, they have been carried out partially by hand, with the help of  CAD drawing tools present in QGIS.



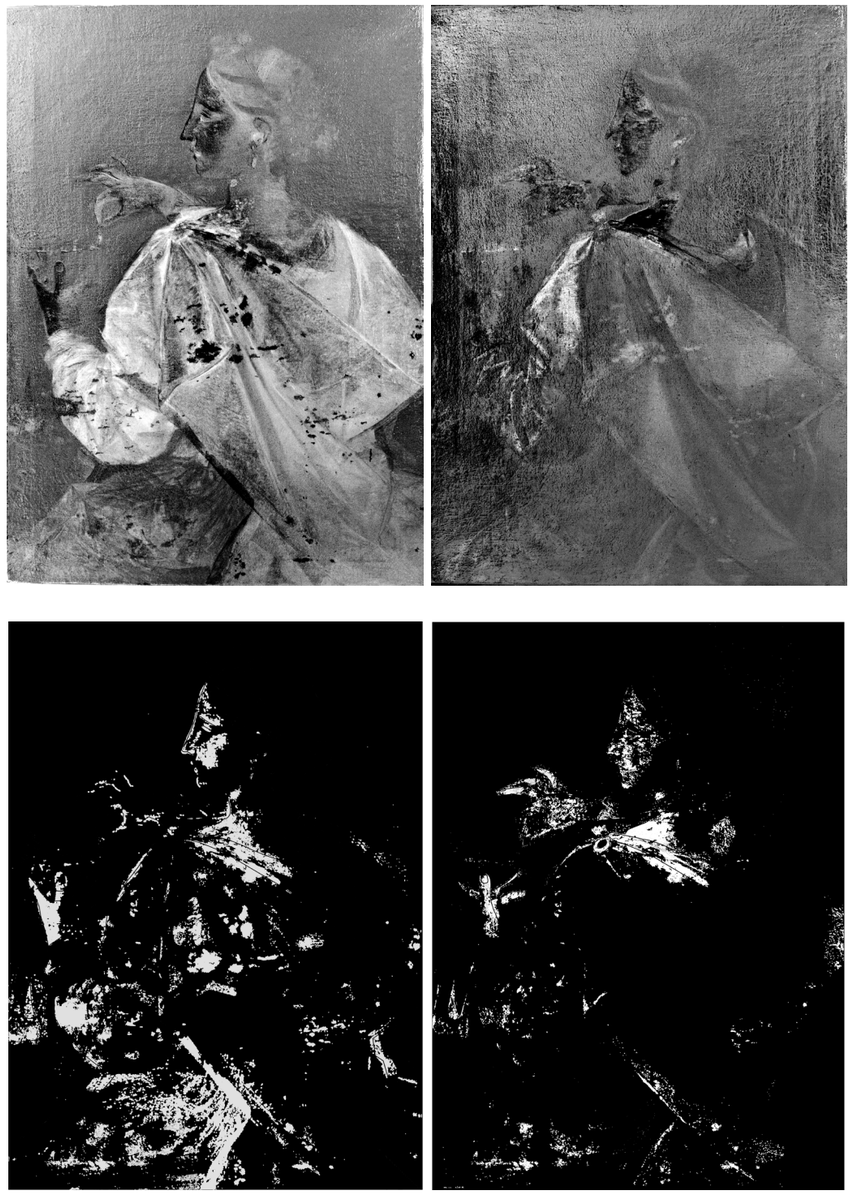


Figure 5.15:
Channels output chosen and respective binary image extracted.

## 5.2.5 Phase II – Stage V: Database Creation

Following the polygons' extraction, we have the second methodology phase, divided into three main stages. Stage V, carried out with QGIS, is essential in all case studies, as it represents the database creation. In this case study, this phase was characterized by a further polygon reclassification step made by the operator. In fact, polygons present in the layer relating to Channel 3 were divided into two separate layers: the first relating to previous conservation interventions, the second to all the lacune found on the artifact (thus to its preservation conditions).

In QGIS this operation can be carried out.

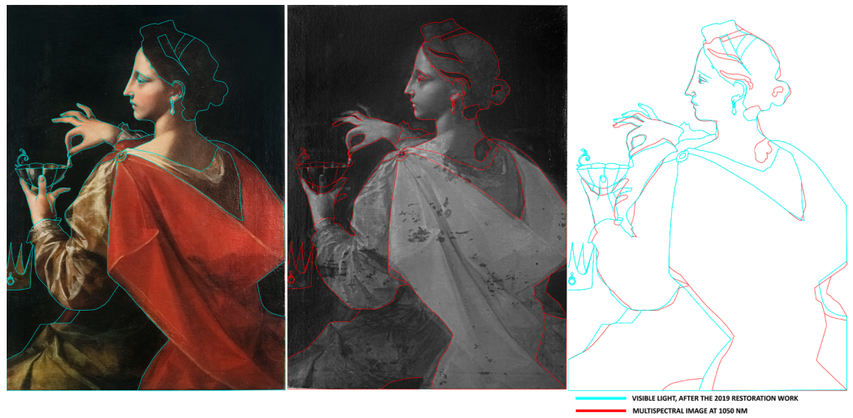
Having registered each extracted polygon to the layer corresponding to its class, alphanumeric data was then associated to them within the attributes table. Next, each polygon and every line were characterized by specific colors and different textures, using characterizing tools from the layers style window.

## 5.2.6 Phase II – Stage VI-VII- Statistical Evaluation, Layout and Storage

In this particular case study, no statistic assessment was carried out on the polygons, thus stage VI in this case was not carried out. However, points corresponding to XRF investigations were inserted, creating a specific attributes table.

The phase corresponding to stage VII was approached directly, consisting in the creation of a printing layout for the final thematic map. Characterization through the attributes table allowed to automatically export the map key concerning points and extracted polygons. All metadata were included in the layout, together with the author's name, the object's dimensions, thematic map serial number, date and documentation executor (Fig. 5.16-17-18).






(a) (b) (c)

Figure 5.16:
Two models of the object. (a) image in the RGB visual range, the final version of the figure, (b) First version of the figure visible in the multispectral image at 1050 nm. (c) Overlap of the two models, the difference between the first version and the final version with the artist's pentimenti.

## 5.2.7 Conclusions and publications

In this case study, methodology integrated and supported the conservation intervention planning, identifying three distinct moments in the history of the artifact and combining canonic XRF and multispectral investigations with image analysis algorithms. In this way, we were able to map and document results much more quickly and accurately than any hand-made graphic documentation.

The work was presented in a poster at the XV Conferenza del Colore dell'Associazione Italiana Colore (Conference on Color of the Italian Color Association). 5-7 settembre 2019, Accademia di Belle Arti di Macerata, and was published on Color Culture and Science Journal [148].

## 5.2.8 Acknowledgments

We wish to thank: the family owning the artifact for allowing us the study and publication; restorer Lucia Palma for the conservation work carried out and for support in recognizing and identifying features relating to the three work moments; Vincenzo Palleschi and Stefano Pagnotta for multispectral shootings and XRF; Emanuele Salerno and Anna Tonazzini for segmentation algorithms application.

Figure 5.17:
Thematic Maps obtained by the automatic extraction of the regions of interest from FastICA raster outputs. For each feature a specific color is assigned.

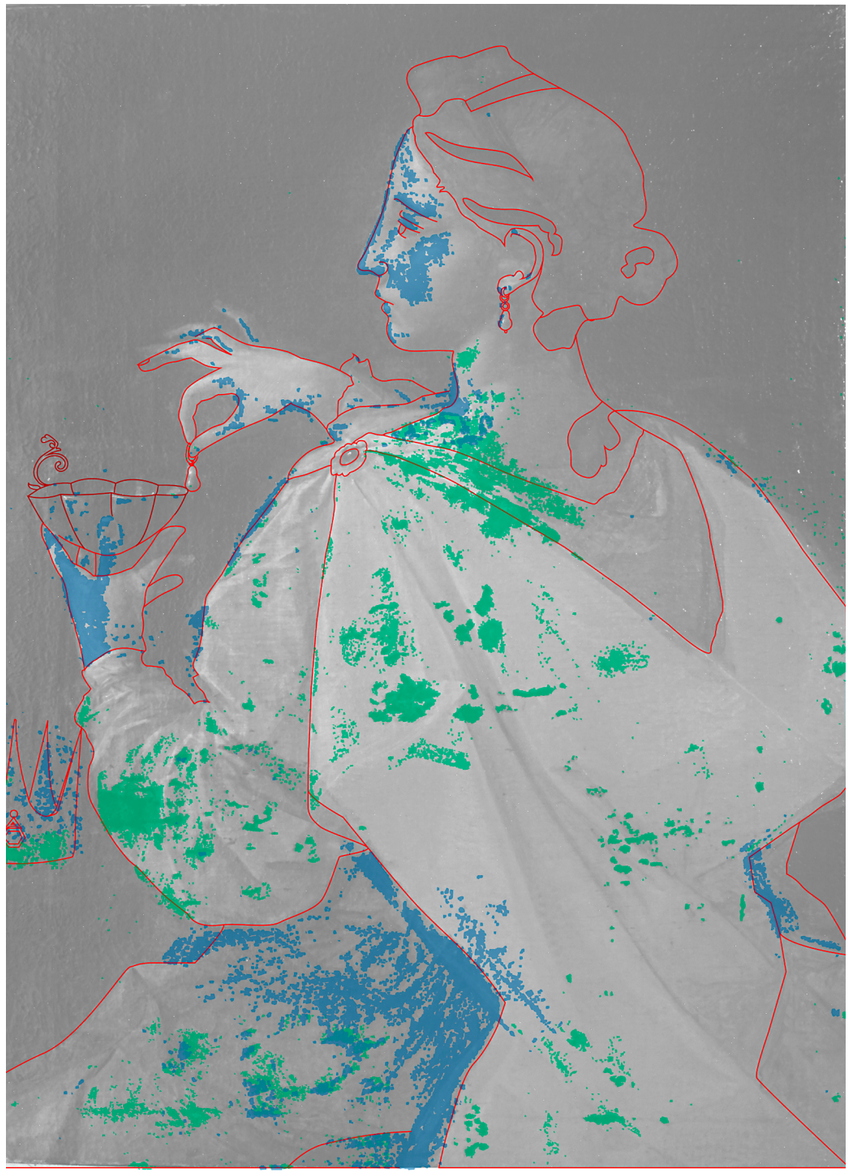





Figure 5.18:
Thematic Maps obtained by the automatic extraction of the regions of interest from FastICA raster outputs. For each feature a specific color is assigned.



# Section 5.3 "Madonna with Child, Saint Joseph and Saint John", anonymous author

The case study presented in this section is characterized by a highly complex analysis, thus some methodology stages have been carried out both in MatLab and in QGIS. To help understanding of the following sections, Table 5.5 recaps the analytical process, indicating with which software each stage was carried out.

Table 5.5. Analytical process, indications of the operations performed in each software.

| PHASE I | |
|---|---|
| **STAGE** | **SOFTWARE** |
| **STAGE II- IMAGE SEGMENTATION** | **MATLAB**<br>*Tool Image Segmenter: Auto Cluster*<br>*Tool Color Thresholder* |
| **STAGE III- IMAGE BINARIZATION** | **MATLAB**<br>*Tool Image Segmenter: Binarization*<br>*Tool Color Thresholder Binarization* |
| **STAGE IV- IMAGE POLYGONIZATION** | **QGIS**<br>*Tool Automatic Raster to Vector* |
| **PHASE II** | |
| **STAGE V- CREATE A DATABASE** | **QGIS**<br>*Table of attributes*<br>*Layers style window* |
| **STAGE VI- STATISTICAL EVALUATION** | **MATLAB**<br>*Tool Image Region Analyzer*<br>**QGIS**<br>*Field Calculator* |
| **STAGE VII- LAYOUT-PRINT-STORAGE** | **QGIS**<br>*Print Layout window*<br>*GeoPakage File* |

Conservation and restoration work for the case study in question was carried out in the canvas Restoration Laboratories of Urbino University[8], the artifact is an oil painting on canvas by the title of "Madonna with Child, Saint Joseph and Saint John", painted around the second half of the Eighteenth century by an unknown Italian artist and belonging today to a private collection. The work was in very poor state of preservation, showing support failure[9], i.e. the support had lost its elastic and mechanical features, and appeared fragile and rigid, the central area presenting a significant tear, extending horizontally from one side to the other and with relevant rips on all the layers, including the support.

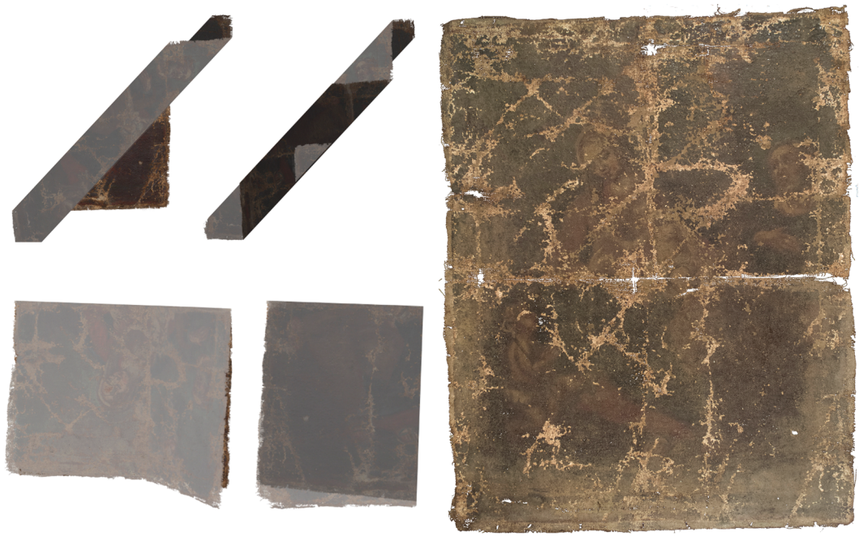
From a structural point of view, these rips were mended during conservation intervention using the thread-by-thread technique [149]. A vast craquelure extended on the whole surface and the entire pictorial film suffered from the Blister and cleavage phenomena, i.e. separation and lifting of the paint film and ground from all layers of the canvas, including support. Such decay phenomena led to numerous lacune and canvas embrittlement[10]. Judging by the morphology and localization of the decay, it can be assumed that the painting was creased in two different ways: one along orthogonal lines, indicating a fold "in four", the other diagonally, indicating rolling up of the canvas itself (Fig. 5.19 a).

Thus, in this particular case study it was necessary to gain a detailed transcription and graphic localization of the preservation state, as the variety of rips and lacune extension and positioning demanded a careful assessment of the reintegration method to be adopted. It was apparent that mere visual analysis would not be sufficient to define the limits within which to apply conservation intervention and would not allow to express a clear overview of conservation problems, nevertheless the classic method of graphic hand transcription appeared inadequate and time consuming, as the edges of the numerous lacunae and rips were irregular and excessive.

8 The work is located at the Restoration Laboratories of the School of Conservation and Restoration - DiSPeA of the Carlo Bo University in Urbino. Conservation and restoration work was carried out as part of the activities related to students Maria Veronica Soro and Giorgia Zantedeschi's qualification test for the Course in Conservation and Restoration of Cultural Heritage - Class LMR/02 a.a. 2018-2019 supervised by restorers Luisa Landi and Luigi Pisani.

9 The original canvas support was made on a vegetable textile support in linen fiber (analyzed with optical microscope and SEM) in a single sheet with plain weave (1: 1) and an average fabric density of 9x9 f / cm2).

10 *Embrittlement*: canvas has become perceptibly fragile to the point of snapping, crumbling or breaking.



(a) (b)

Figure 5.19:
Madonna and Child, St. Joseph and St. John by an unknown artist, oil on canvas, second half of the Eighteenth century, 77x61cm.
(a) The hypothesis of two different folds of the canvas
(b) The canvas before restoration.



Figure 5.20:
Madonna and Child, St. Joseph and St. John by an unknown artist, oil on canvas, second half of the Eighteenth century, 77x61cm
The canvas after conservation/restoration: consolidation and cleaning.



## 5.3.1 Phase I-Stage I: Image acquisition

The work was captured in two different moments, both in ultraviolet induced fluorescence and in infrared (780-950 nm, NIR), from which a fake color was extracted. In addition, various shots in visible light were captured before, after and during the intervention. Having observed the UV fluorescence investigation carried out before intervention, it appeared evident that the thick overlayer of dust and mud didn't allow a good fluorescence response, and it was decided to repeat investigation after a cleansing operation on the superficial hydrophilic layer. The second fluorescence image allowed to identify the presence of filmogenous layers on the painting's surface and to gain important information on the layers' brush-strokes and their orientation oblique. Based on the yellow-green fluorescence tones, characterized by low light intensity, it can be assumed that such brush-strokes were made of a natural resin based varnish. Still in this second acquisition session, near infrared reflectography (780-980 nm, Fig. 5.22 b) highlighted the contrasts between the painting's light and shadow brush-strokes, defining outlines and a few details on the figures hardly observable in visible light. Furthermore, it was possible to more clearly identify the lacunae and rips' edges.

| Investigation | Camera | Filter | Irradiation | Reference |
|---|---|---|---|---|
| acquisitions before the restoration | | | | |
| Ultraviolet-induced luminescence (UVL) | Canon EOS 60D Nikon D90 FR | B&W 022 Hoya X0, Hoya Sepia A | N.2 Lamp Madatec UV | Color checker KODAK color control Patches |
| Infrared-reflected (NIR) | | IR850 | N.2 Osram Nitra phot bm 500w | KODAK Gray Scale |
| acquisitions during restoration | | | | |
| Ultraviolet-induced luminescence (UVL) | Nikon D800 | Hoya IRUV cut | N.2 Lamp Madatec UV | Colo chart X-RITE Reference 99% Minolta not-fluorescent; parasite light subtraction |
| IR 780-980nm | Nikon D800IRUV | Peca 87c | N.2 Osram Nitra phot bm 500w | Colo chart X-RITE |

Table 5.6:
Modalities and equipment for the acquisition of diagnostic investigations

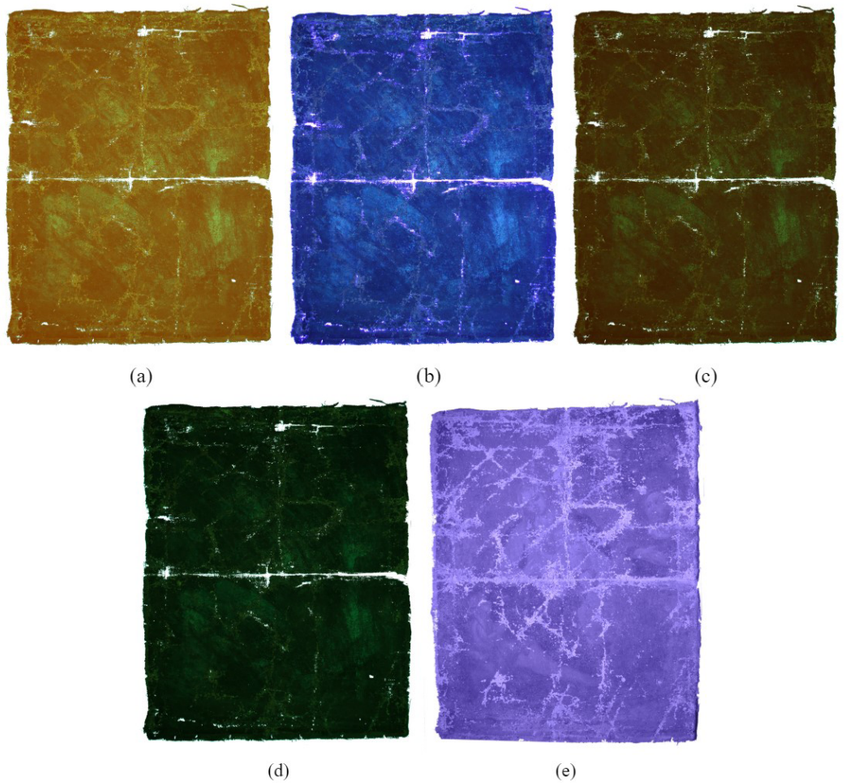



Figure 5.21:
Madonna and Child, St. Joseph and St. John by unknown artist, acquisitions before the restoration.
(a) Visible light
(b) Fluorescence induced.
Images acquired and processed by Mauro Torre.

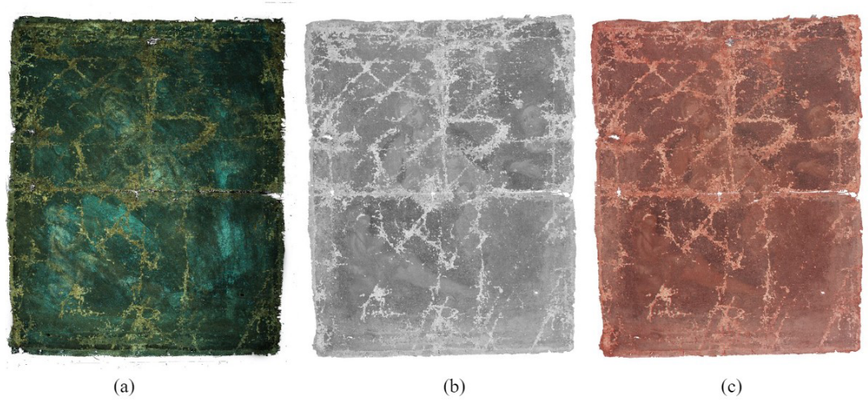



Figura 5.22:
Madonna and Child, St. Joseph and St. John by unknown artist, acquisitions after cleaning the most superficial layer of hydrophilic nature.
(a) Induced Fluorescence
(b) NIR
(c) False Color
Images acquired and processed by Paolo Antonio Maria Triolo.



## 5.3.2 Phase I-Stage II-III: Image analysis with segmentation algorithms and Binarization

The acquired diagnostic images weakly show their characteristics through gray-scales or dominant tones which nevertheless coexist within each individual channel. This aspect, especially in complex cases such as the one presented, may lead to characteristics being difficult to read and distinguish. In this case study it was necessary to identify and visually select in an evident way two characteristic categories, relating to previous interventions and to the preservation conditions, as listed in table 5.6.

| CATEGORIES | |
|---|---|
| PREVIOUS INTERVENTIONS | STATE OF PRESERVATION |
| FEATURES | |
| Varnish application prior or posthumous to the loss of the paint film<br><br>Concentration and orientation of non-original varnish application. | Lacunae in the pictorial film<br><br>Missing areas in the preparatory layer<br><br>Presence of material on top of the original;<br><br>Percentage of the missing areas. |

Table 5.7:
Classification of the characteristics to be found divided by categories.

Considering consistent complexity of the features to be identified, various tests were carried out in this stage using segmentation algorithms from the MatLab software, which provide for automatic extraction of binary masks. This is why Stage II and III appear together in this section. Also, for this case study we decided to try and carry out segmentation also on the visible image provided after restoration, considering that in it a group of researched features was already evident. This test allowed to proof that this methodology can also be applied to images acquired in visible light, as diagnostic investigation tools are not always available to restorers [150][151][152].

### 5.3.2.1 Image Segmenter of visible light trough Auto Cluster tool

A first test was carried out using only the visible image acquired after the restoration using the tools in the MatLab Image Segmenter toolbox, in particular using the Auto Cluster tool and the Morphological Operators. We used an image with a completely white background; this feature allowed us to separate the area of the pigmented canvas from the area of the lacunae with a single click using Auto Cluster. Once the desired result was obtained, the segmentation was automatically converted into a binary mask and was exported from Matlab and used for the next stages of the methodology.

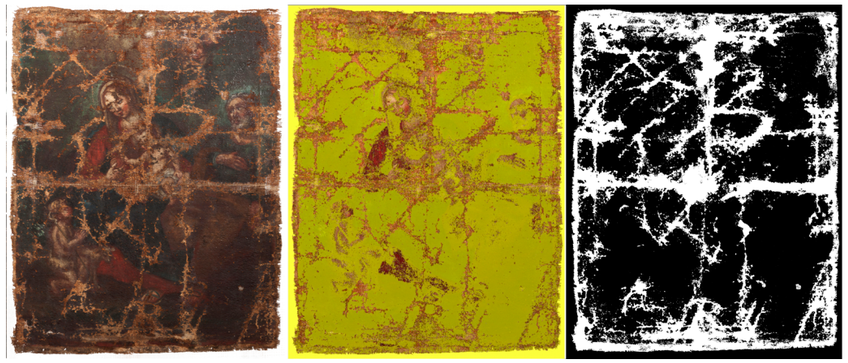


Figura 5.23:
(a) image in visible light after restoration
(b) image during the "auto cluster" segmentation
(c) logical image in output

### 5.3.2.2 Image Analysis trough Blind Source Separation (BSS) algorithms

Following second stage in conformity with methodology, we applied the statistics analysis technique (BSS) to the group of acquired diagnostic images; in particular we used the PCA or principal component analysis and ICA or independent component analysis techniques. Statistic elaboration was carried out entirely using Matlab software, with all diagnostic images acquired before and during intervention as input. Images were elaborated in two separate groups as, having been taken with two different kinds of equipment and in two separate moments of the support conservation process, they did not guarantee a full consistency and match between them; which is a necessary characteristic for statistic elaboration.
In Tables 5.7 and 5.8 the elaboration system carried out in two separate moments



is recapped: for each algorithm, the images divided into two groups were elaborated first individually and then simultaneously, in one solution. Concerning the group of images taken before intervention (Fig. 5.21), in output from the individual and simultaneous elaborations we gained in total 48 channels (grayscale images). For the group relating to images taken during intervention (Fig. 5.22) we gained 24 channels in output.

| FIRST DIAGNOSTIC ACQUISITIONS | | | |
|---|---|---|---|
| ALGORITHMS USED | INPUT IMAGES INDIVIDUALLY ANALYZED | N°CHANNELS Output grayscale images | PSEUDO COLOR RGB Combination of three grayscale channels |
| ICA *independent component analysis* | UV filter BW020 | 3 | PSEUDOCOLOR |
| | UV Filter Hoya Sepia A | 3 | PSEUDOCOLOR |
| | UV filter Hoya X0 | 3 | PSEUDOCOLOR |
| | UV none Filter | 3 | PSEUDOCOLOR |
| PCA *principal component analysis* | UV filter BW020 | 3 | PSEUDOCOLOR |
| | UV Filter Hoya Sepia A | 3 | PSEUDOCOLOR |
| | UV filter Hoya X0 | 3 | PSEUDOCOLOR |
| | UV none Filter | 3 | PSEUDOCOLOR |
| ALGORITHMS USED | INPUT IMAGES INDIVIDUALLY ANALYZED | N°CHANNELS Output grayscale images | |
| ICA *independent component analysis* | UV filter BW020<br>UV Filter Hoya Sepia A<br>UV filter Hoya X0<br>UV none Filter | 12 | |
| PCA *principal component analysis* | UV filter BW020<br>UV Filter Hoya Sepia A<br>UV filter Hoya X0<br>UV none Filter | 12 | |
| SECOND DIAGNOSTIC ACQUISITIONS | | | |

Table 5.8:
Summary of statistical processing performed with ICA and PCA on images taken before restoration.

Table 5.9:
Summary of statistical processing performed with ICA and PCA on images taken during restoration.

| ALGORITHMS USED | INPUT IMAGES INDIVIDUALLY ANALYZED | N°CHANNELS Output grayscale images | PSEUDO COLOR RGB Combination of three grayscale channels |
|---|---|---|---|
| ICA *Independent component analysis* | UV filter Hoya IR UV Cut | 3 | PSEUDOCOLOR |
| | false-color (IR 780-980) | 3 | PSEUDOCOLOR |
| PCA *principal component analysis* | UV filter Hoya IR UV Cut | 3 | PSEUDOCOLOR |
| | False-Color (IR 780-980) | 3 | PSEUDOCOLOR |
| ALGORITHMS USED | INPUT IMAGES INDIVIDUALLY ANALYZED | N°CHANNELS Output grayscale images | PSEUDO COLOR RGB Combination of three grayscale channels |
| ICA *Independent component analysis* | UV filter Hoya IR UV Cut False-Color (IR 780-980) | 6 | *PSEUDOCOLOR* |
| PCA *principal component analysis* | UV filter Hoya IR UV Cut False-Color (IR 780-980) | 6 | |

### 5.3.2.3 Pseudo-color: creation and analysis

In this case study, concerning the first group of images, in output from individual elaborations we obtained 4 pseudo-color/ICA images and 4 pseudo-color/PCA images formed of 3 channels each.

For the images acquired in the second phase, we obtained in output 2 pseudo-color/ICA, and 2 pseudo-color/PCA from the output channels of induced fluorescence and from output channels of fake color. Figure 5.25 and 5.26 shows some areas representative of the researched features.

The first to be analyzed concerns the varnish layer application: if from the ultraviolet fluorescence images the paint strokes distribution ductus could already be appraised, in the pseudo-color images, (gained through elaboration on the group of pre-restoration images), the areas with a stronger varnish density are highlighted in bright green, and in pale blue and pale green the ones in which varnish is less present. The latter, also corresponding to areas of loss, clarify any doubts about the timing of varnish application prior or posthumous to the loss of the paint film (Fig.5.25). Also, the grayscale channels clarify varnish distribution with stronger contrasts, highlighting it in black (Fig. 5.24). As for the features related



to the lacunae area in the pictorial film, statistic elaborations carried out on the group of images taken during intervention allowed us to assess the ground stratigraphy, identifying three kinds of lacunae: visible canvas, ground with organic medium and natural inert materials[11], chromatic priming[12](Fig. 5.26).

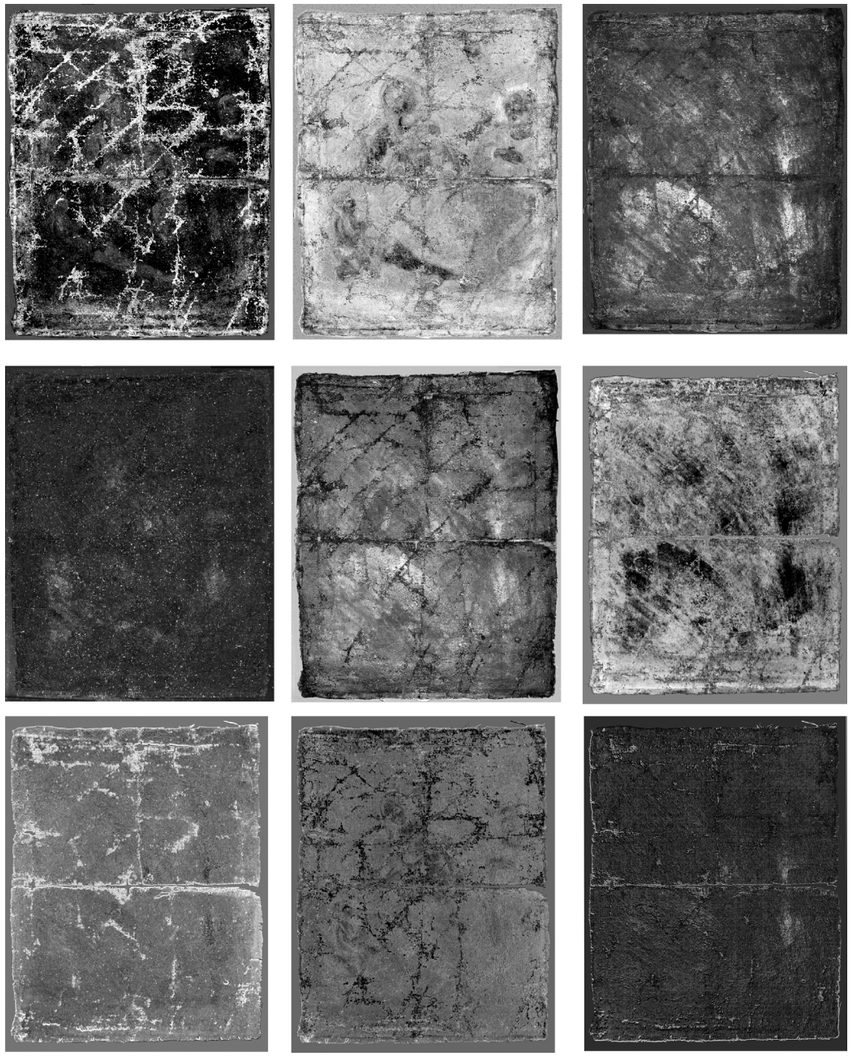


Figura 5.24:
Some of the 72 grayscale channels output from PCA and ICA statistical processing. In these selected channels, the sought-after features are highlighted strongly.

11 The term *ground* is used to define the first layers applied to the canvas support to obtain an appropriate surface to receive pictorial pigments.

12 The term *priming* is used to indicate the finishing layer of the *ground* allowing for easy application of brush strokes and giving the paint layers a transparent or opaque base color.

Figure 5.25:
Example of pseudocolor resulting from statistical analysis of diagnostic images acquired before restoration.

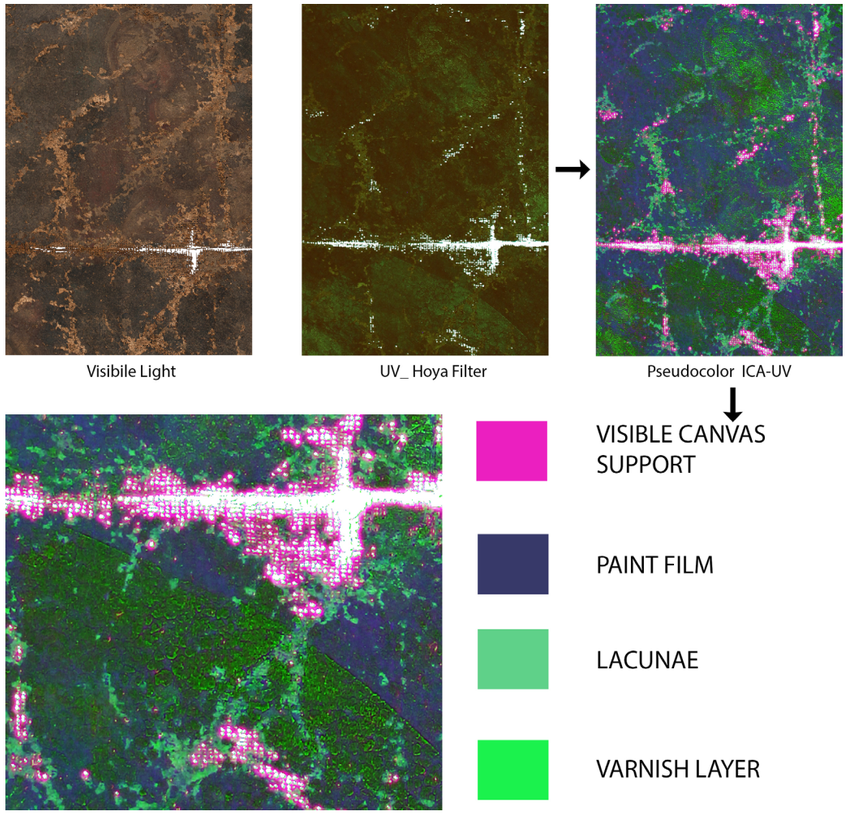
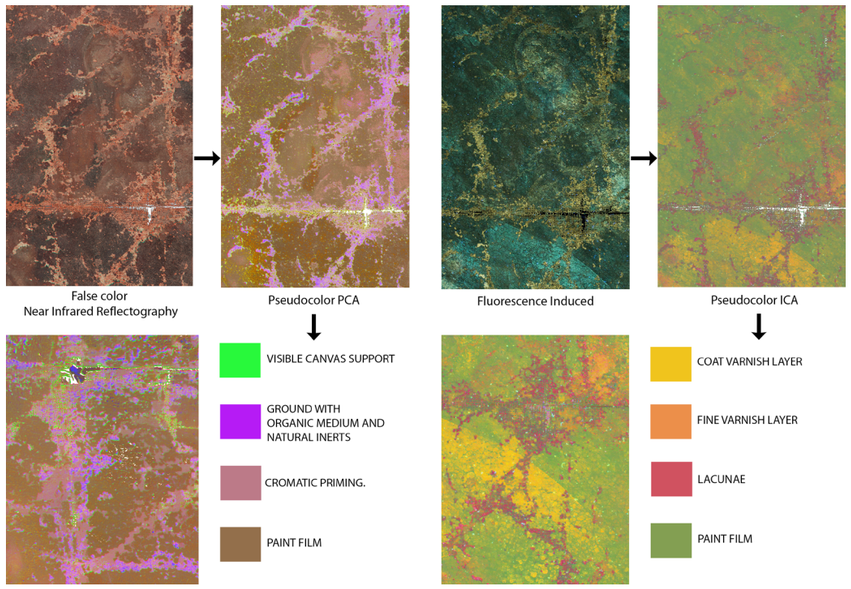



Figure 5.26:
Example of pseudocolor resulting from the statistical analysis of the diagnostic images performed during the restoration.






### 5.3.2.4 Extraction of binary masks from pseudo-color

Segmentation of Pseudo-color images for the extraction of binary masks were carried out in MatLab using the Color Thresholder tool from the image processing toolbox. This tool was particularly useful in the segmentation of color images, as it allows an iterative approach, through a trial and repetition process up to the desired result [153]. Segmentation can be tested in different color spaces (Fig.5.27), as a space could isolate a color more than another; to begin with, an automatic segmentation can be carried out, selecting a region of interest to then perfection it using the color component controls provided by the app (Fig.27) [134]. In this case, we chose to segment pseudo-color images in the HSV (Hue, Saturation, value, also known as HSB or Hue, Saturation, Brightness) space. We thus grouped the researched features in groups of pixels with similar properties.

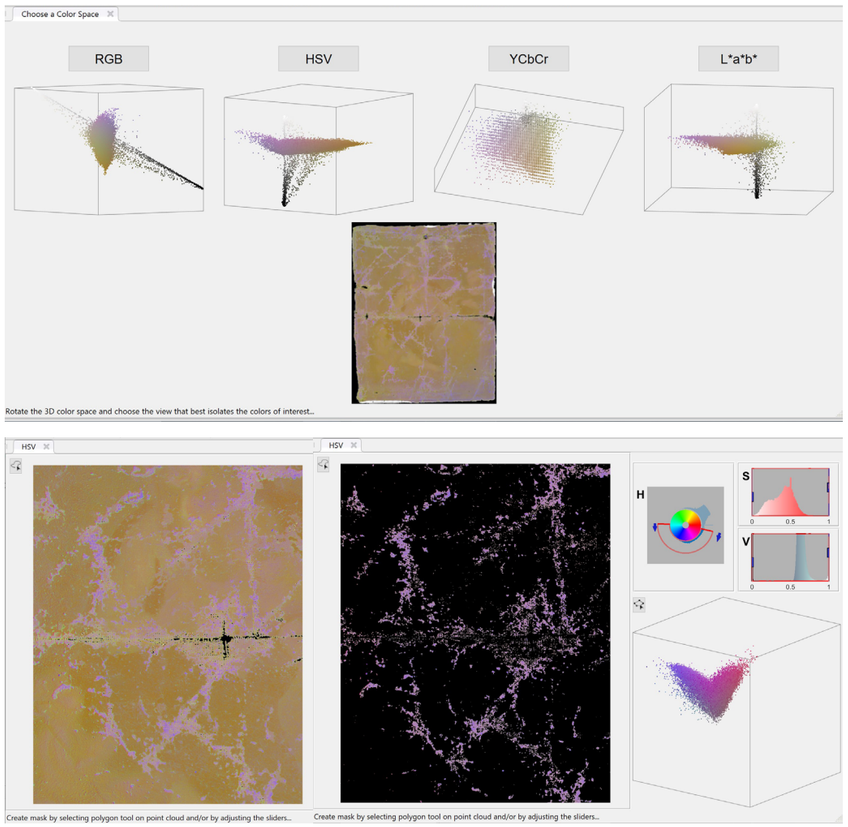



Figure 5.27:
Matlab screenshot. Color Tresholder app. Segmentation of pseudo-color on HSV model.

## 5.3.3 Phase I-Stage IV: Conversion from raster to vector

Carrying on with the fourth stage, a QGIS project was created, importing both the acquired images and the binary masks exported by Matlab. All images were imported with the word-file method. Thus, it was possible to carry on with conversion of binary masks into vectorial polygons with the automatic polygonizer from raster to vector tool. On the whole, 5 polygonal layers were created corresponding to the researched features.

***Preservation conditions Category:***

***Layer 1:*** polygons related to overall gaps and lacerations.
For this layer we selected the binary mask extracted from the visible light image taken after restoration.
***Layer 2:*** polygons related to the gaps in the ground layer that show the canvas support. For the creation of this layer we used the binary mask extracted from the pseudo-color/PCA from the false NIR color performed after restoration.

***Previous interventions Category:***

***Layer 3:*** polygons related to the application of non-original varnish.
For the creation of this layer we used the binary mask extracted from the pseudo-color/ICA image coming out of the Ultraviolet Fluorescence performed after restoration.

***Executive techniques Category:***

***Layer 4:*** polygons related to that show the chromatic priming.
***Layer 5:*** polygons related to lacunae area in the pictorial film that show the ground with organic medium and natural inert materials. For the creation of this layer we used the binary mask extracted from the pseudo-color/PCA from the false NIR color after restoration.



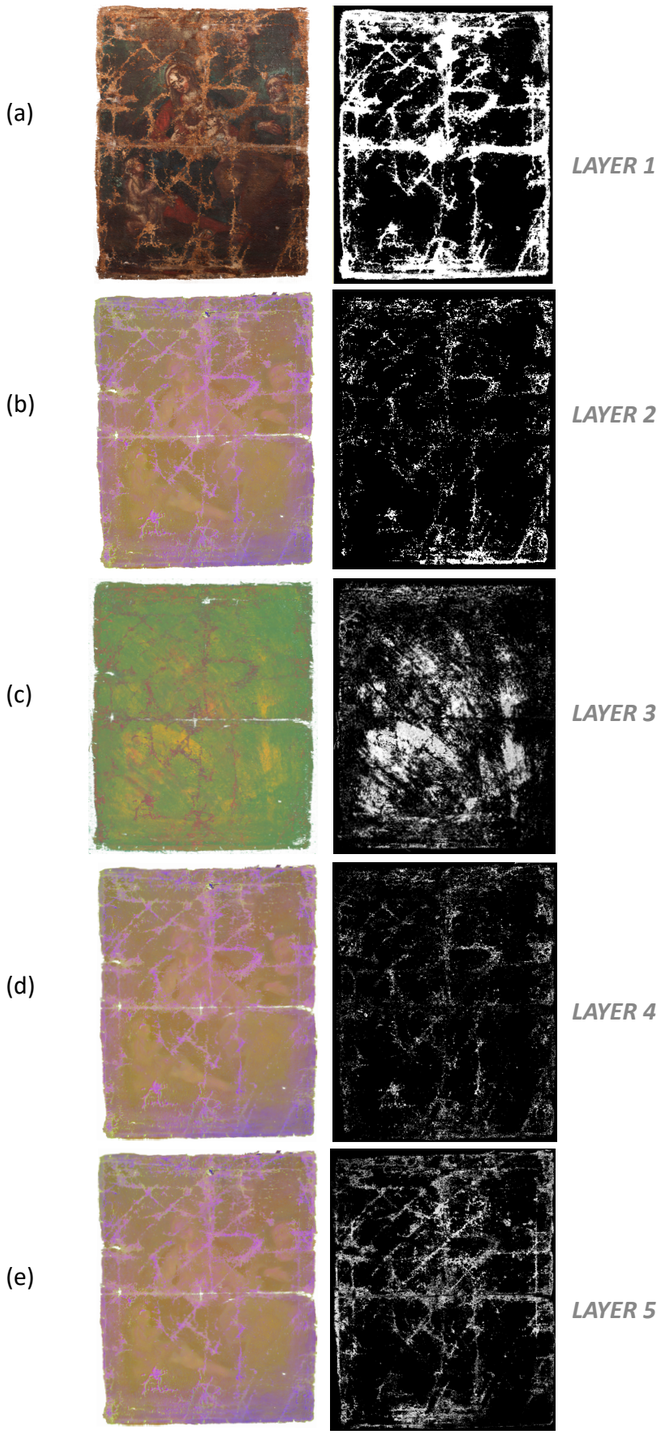



Figure 5.28:
Images used to extract searched features, respective binary images extracted with Color Tresholder app.

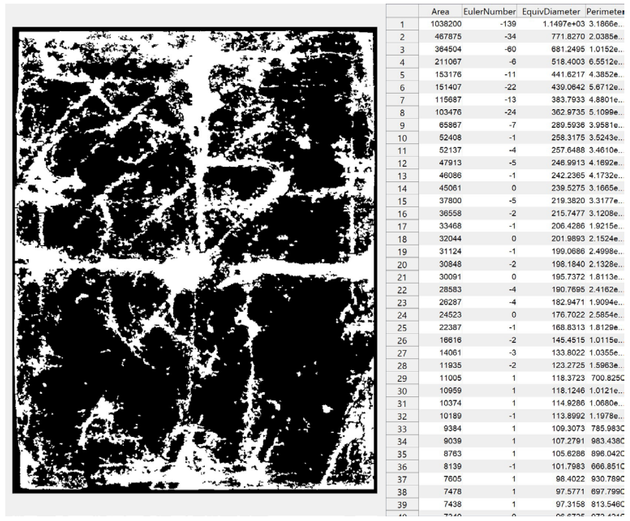
## 5.3.4 Phase II – Stage VI-VII- Statistical Evaluation, Layout and Storage

Statistic assessment phase was carried out both in Matlab and in QGIS, whereas the thematic maps layout phase was carried out exclusively in QGIS.

### 5.3.4.1 Matlab: analysis of the lacunae areas

The binary mask obtained through segmentation of the visible light image was analyzed using the Image Region Analyzer tool from the MatLab image elaboration toolbox. This tool turned out as particularly useful to the cause of lacunae analysis, especially in complex case studies such as ours. Classification criteria can be subjectively assessed by conservators-restorers, as each case study may require different classifications, not necessarily based on area calculation.

In our case, various classification hypothesis were considered, including that of subdividing lacunae into 3 classes: small, medium and large (Fig.5.30). Region grouping values were chosen by interrogating the binary image and assessing the positioning of lacunae on the canvas surface. The larger lacunae group was further divided into two groups, depending on their position within the representation: lacunae that are difficult to reintegrate, (mostly on the figures) and lacunae that are easy to reintegrate [154] [133] [94].



| | Area | EulerNumber | EquivDiameter | Perimeter |
|---|---|---|---|---|
| 1 | 1038200 | -139 | 1.1497e+03 | 3.1866e... |
| 2 | 467875 | -34 | 771.8270 | 2.0385e... |
| 3 | 364504 | -60 | 681.2495 | 1.0152e... |
| 4 | 211067 | -6 | 518.4003 | 6.5512e... |
| 5 | 153176 | -11 | 441.6217 | 4.3852e... |
| 6 | 151407 | -22 | 439.0842 | 5.6712e... |
| 7 | 115687 | -13 | 383.7933 | 4.8801e... |
| 8 | 103476 | -24 | 362.9735 | 5.1099e... |
| 9 | 65867 | -7 | 289.5936 | 3.9581e... |
| 10 | 52408 | -1 | 258.3175 | 3.5243e... |
| 11 | 52137 | -4 | 257.6488 | 3.4610e... |
| 12 | 47913 | -5 | 246.9913 | 4.1892e... |
| 13 | 46086 | -1 | 242.2365 | 4.1732e... |
| 14 | 45061 | 0 | 239.5275 | 3.1665e... |
| 15 | 37800 | -5 | 219.3820 | 3.3177e... |
| 16 | 36558 | -2 | 215.7477 | 3.1208e... |
| 17 | 33468 | -1 | 206.4286 | 1.9215e... |
| 18 | 32044 | 0 | 201.9893 | 2.1524e... |
| 19 | 31124 | -1 | 199.0686 | 2.4998e... |
| 20 | 30848 | -2 | 198.1840 | 2.1328e... |
| 21 | 30091 | 0 | 195.7372 | 1.8113e... |
| 22 | 28583 | -4 | 190.7695 | 2.4162e... |
| 23 | 26287 | -4 | 182.9471 | 1.9094e... |
| 24 | 24523 | 0 | 176.7022 | 2.5854e... |
| 25 | 22387 | -1 | 168.8313 | 1.8129e... |
| 26 | 16816 | -2 | 145.4515 | 1.0115e... |
| 27 | 14061 | -3 | 133.8022 | 1.0355e... |
| 28 | 11935 | -2 | 123.2725 | 1.5963e... |
| 29 | 11005 | 1 | 118.3723 | 700.8250 |
| 30 | 10959 | 1 | 118.1246 | 1.0121e... |
| 31 | 10374 | 1 | 114.9286 | 1.0680e... |
| 32 | 10189 | -1 | 113.8992 | 1.1978e... |
| 33 | 9384 | 1 | 109.3073 | 785.9830 |
| 34 | 9039 | 1 | 107.2791 | 983.4380 |
| 35 | 8763 | 1 | 105.6286 | 898.0420 |
| 36 | 8139 | -1 | 101.7983 | 666.8510 |
| 37 | 7605 | 1 | 98.4022 | 930.7890 |
| 38 | 7478 | 1 | 97.5771 | 697.7990 |
| 39 | 7438 | 1 | 97.3158 | 813.5460 |

Figure 5.29:
Screen shot of Matlab, Image Region Analyzer app. Binary image of overall area relative to gaps with corresponding table.



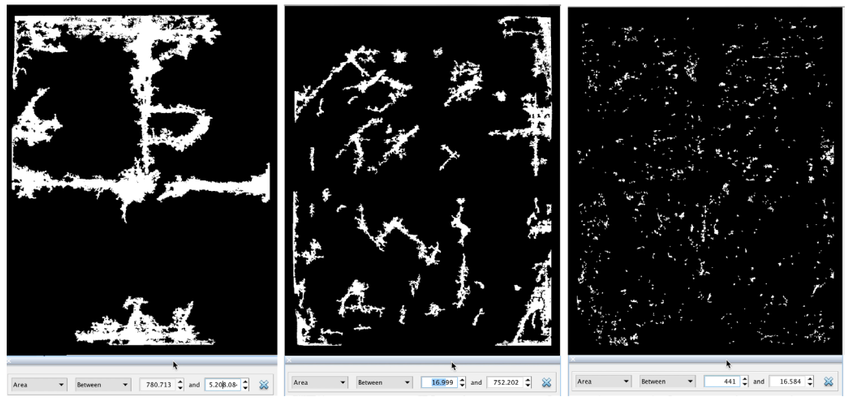



Figure 5.30:
Screen shot of Matlab, Image Region Analyzer app. Dividing the lacunae into small medium and large. Classification performed with Boolean operators using area value.

### 5.3.4.2 Calculation of the overall percentage of the lacunae, tear and rips area

To guide restorers in their intervention, percentage of the total lacunae area was calculated as opposed to the canvas surface. Independently from spatial acquisition resolution, each artifact reproduction must respect the original dimensions in 1:1 scale, to allow an accurate analysis also in digital reality. In fact, only real measures allow accurate results. As each lacuna area is represented in MatLab by pixel units, the first step is to determine the total loss area in cm2 (ALc), by adding up all the lacunae pixel areas (ALp):

$$AL_p = \sum_{i=1}^{N} AL_i \tag{29}$$

In which Ali represents the area of i-N lacunae.

The next phase consists in determining total loss surface in cm2 through the following relation:

$$AC_c \geq AC_p = x : AL_p$$
$$x = \frac{AC_c \times AL_p}{AC_p} \tag{30}$$

In which Acc is the canvas area in cm2, Acp is the canvas area in pixels, x is ATc , i.e. total lacunae area in cm2. We can thus obtain area measures expressed in cm2 and in percentage through the following formula:

$$AL_C : AC_c = x : 100 \tag{31}$$

Data gained from statistic assessment have shown that percentage of missing areas, around 29%, occupied almost a third of the painting's total surface. This information encouraged restorers to exclude the lacunae filling intervention, as the necessary material would have added an excessive weight onto the support, causing a painting shrinking.

Table 5.10:
Area values in pixels and cm regions of interest

| CANVAS AREA AND LACUNAE AT 300 PIXELS PER INCH OF RESOLUTION | | |
|---|---|---|
| CANVAS | cm | pixel |
| $(AC)$ Canvas area | $(AC_c)$ 4.534 Cm$^2$ | $(AC_p)$ 65522270 pixel |
| LACUNAE | cm | pixel |
| $(AL)$ Lacunae area | $(AL_c)$ 1.334 Cm$^2$ | $(AL_p)$ 18610183 pixel |

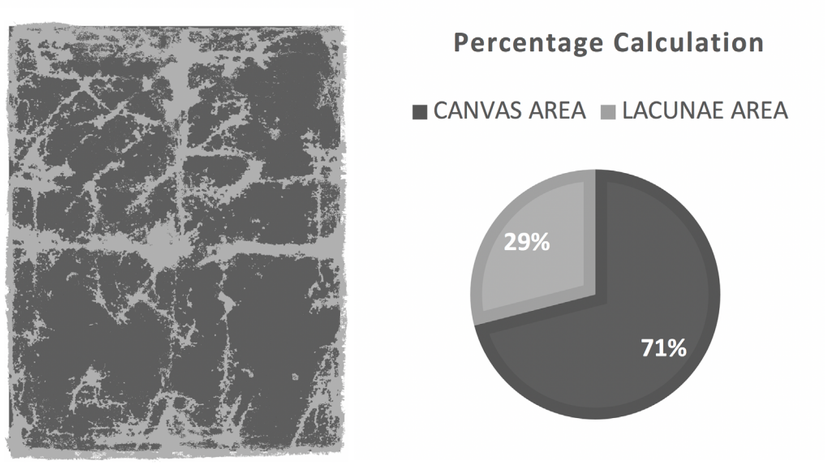



Figure 5.31:
Screen shot of Matlab, Image Region Analyzer app. Dividing the lacunae into small medium and large. Classification performed with Boolean operators using area value.

### 5.3.4.3 Statistical analysis in QGIS

In QGIS the percentage of the area was calculated in the attribute table with the field calculator, as shown in section 4.6. For statistical evaluations QGIS is certainly much easier to use than Matlab as it allows for scaled measurements with units in meters.



## 5.3.5 Proposals for virtual pictorial reintegration

Having carried out all necessary analysis, we moved on to the project of lacunae pictorial reintegration. To help restorers in their executive choices, various virtual inpainting proposals were made [155].

### 5.3.5.1 Calculation of the zonal statistical average

The first phase of this process consists in identifying the neutral tones present on the canvas, in this case we used a zonal statistical average function on the visible light image taken after restoration. We then calculated the mean value of the entire canvas area excluding the lacunae, tear and rips areas which didn't present any pigment, obtaining a set of three RGB values (Mv RGB), which represent the average of colored pigments existing on the canvas [133].
For a variable casual vector A made of N observed scalar data, the average is defined as

$$\mu = \frac{1}{N}\sum_{i=N}^{N} A_i$$

Thus the average of RGB values can be represented through the following expression, in which M corresponds to the mean value and v to the values:

$$M_v\,RGB = \left[ M_{Rv} = \frac{1}{N}\sum_{i=1}^{N} R_i, M_{Gv} = \frac{1}{N}\sum_{i=1}^{N} G_i\ , M_{Bv} = \frac{1}{N}\sum_{i=1}^{N} B_i \right] \tag{32}$$

$$M_v\,RGB = R = M_{Rv}\ , G = M_{Gv}, B = M_{Bv}$$

### 5.3.5.2 Execution of virtual intervention proposals

The different lacunae inpainting proposals were carried out with Adobe Photoshop©13 CC2019, using the color substitution technique and modifying the lacunae RGB values with the average values obtained. Binary masks extracted in Matlab© were used to select and substitute only pixels from relevant areas, thus respecting the minimum intervention principle in due respect of the original canvas area.

13 Adobe® Photoshop® CC Help, latest update 2/2/2018

The virtual reintegration process was carried out in steps and with various techniques:

***Pictorial reintegration Technique with optical-tonal lacunae attenuation***

***Step 1:*** simulation of chalk and glue filling as shown in figure 5.32 (a) was simulated by simply using a complete white filling with the bucket tool.

***Step 2:*** next reintegration with neutral tones obtained from the statistic average of all the area with pictorial film was proposed.

***Step 3:*** using the latter neutral tone as model, a lighter one was applied on the visible parts of the canvas.

***Step 4:*** in the last phase a further neutral tone was made by using a texturized filling, similar to the craquelure.

***Mimetic reintegration Technique***

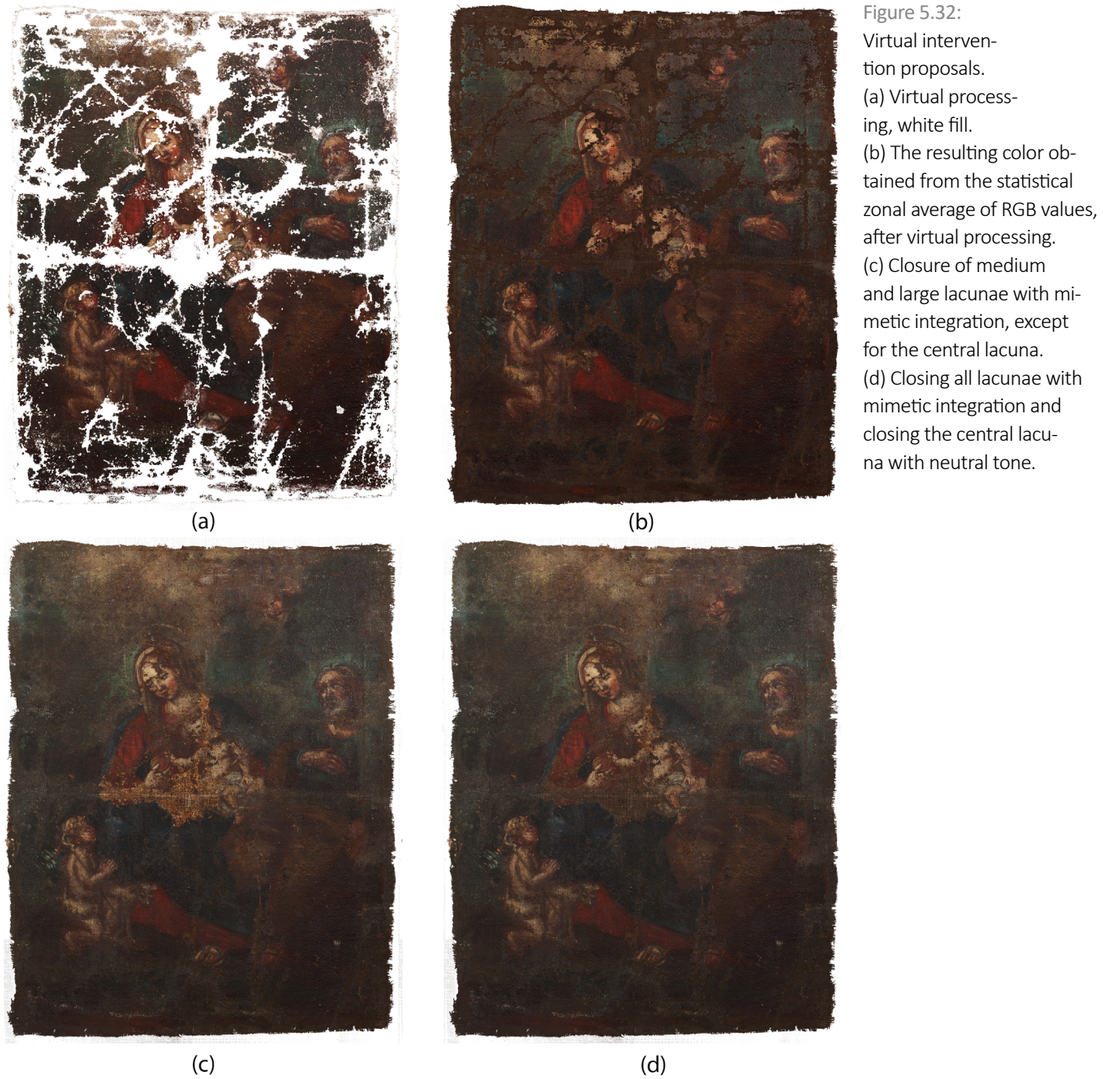
As results with the average tone were not visually pleasing, it was decided to "close" all the smaller lacunae with a mimetic reintegration.

***Step 5:*** all easily integrated lacunae, characterized by flat campitura and even colors, and mainly localized on the background and on figurative elements easy to recognize and reconstruct, were closed mimetically [156]. This allowed to eliminate the visual disturb and to carry on with analysis of the remaining lacunae (Fig.5.32 c).

***Step 6:*** next, various mimetic pictorial integration proposals were created, following the previous lacunae classification in small, medium and large. In particular, a mimetic tone was used for medium lacunae and a neutral tone for large lacunae.

In this step, the central lacuna concerning the Madonna and Child figures was treated differently because of its extension and the relevant figurative elements, difficult to reconstruct. For this lacuna, both a neutral tone and visible canvas were proposed.



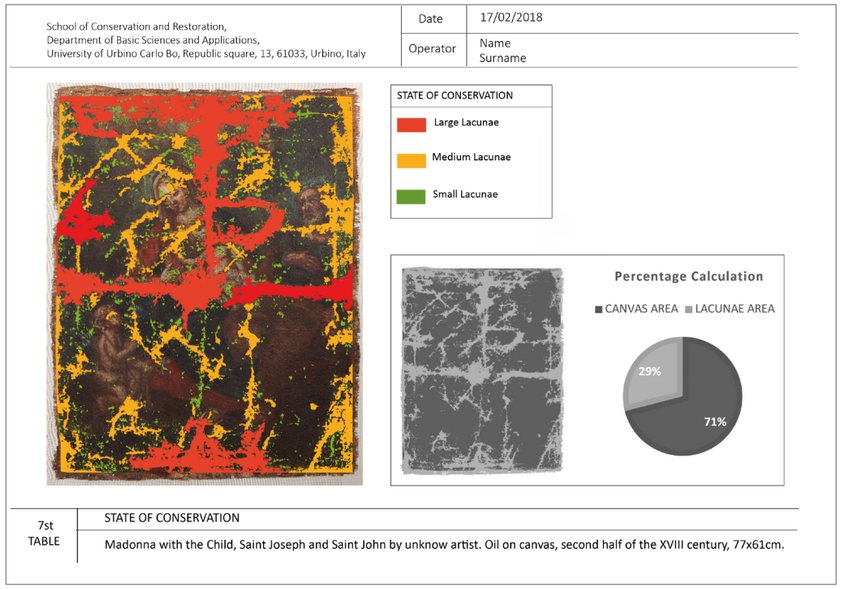


(a) (b) (c) (d)

Figure 5.32:
Virtual intervention proposals.
(a) Virtual processing, white fill.
(b) The resulting color obtained from the statistical zonal average of RGB values, after virtual processing.
(c) Closure of medium and large lacunae with mimetic integration, except for the central lacuna.
(d) Closing all lacunae with mimetic integration and closing the central lacuna with neutral tone.

Figure 5.33:

Example of thematic mapping obtained with the automatic extraction procedure and layout in QGIS.






## 5.3.6 Conclusions and publications

Study of diagnostic images and of statistic elaboration carried out on them has allowed us to gain a scientific reference support to elaborate operative restoration choices, obtaining a detailed and objective graphic base of the missing areas. In particular, it was possible to single out areas in which there was total loss, i.e. in which all layers were affected, from those in which the preparatory layer was still present. Varnish paint-strokes graphics extracted from UV pseudo-color allowed us to identify where they were mostly concentrated, observing different thickness of overlayed material and taking this into account during cleansing operation, thus carried out with a more aware scientific approach. The applied methodology also showed that the lacunae percentage (about 29%) was much too high to allow integration of the missing preparatory layers. Furthermore, semi-automatic extraction of the lacunae area allowed us to carry out a virtual iconographic restoration intervention, assessing different inpainting intervention hypothesis without ever modifying the original canvas image pixels, thus respecting recognizability and minimum intervention principles. In brief, we consider useful developing a methodology which can support diagnostics and documentation, relying on information technologies for digital image analysis and on GIS, and which allows to improve and automatize the artifact's study process, with the creation of vectorial files, guiding restorers in their intervention choices, leading to a consistent esthetic presentation.

This work was presented in an oral address at the 5TH Edition of the International Meeting on Retouching of Cultural Heritage organized by RECH GROUP in 2019 at the Carlo Bo University in Urbino, and was published on GE-Conservation Journal in 2020 [157]. In 2020 the project participated in a competition organized by Kermes magazine and by ANED – Cultural Heritage association, gaining second place and thus participating through a video presentation at the 2020 Salone dell'arte e del Restauro (Art and Conservation exhibition)[14].

14 https://www.salonerestaurofirenze.com/restauro/2020/la-diagnostica-al-servizio-dei-beni-culturali-e-del-restauro-premio-in-memoria-di-andrea-galeazzi/

# Conclusions

This work presents a new methodological approach, finalized to semi-automation of current graphic documentation procedures for cultural heritage conservation and restoration. The aim was to offer a concrete contribution in answer to the lack of software tools sustaining conservators/restorers in diagnostic image analysis, in features' extraction and in the creation of thematic maps. Currently, such operations are carried out in a rather generic way, due to the obliged manual approach of the software in use. Digital image  elaboration software combined with geographic information systems represent an effective solution to current documentation problems. In particular, Free and Open Source QGIS geographic information system has proven to be a unique and highly useful User-Friendly system, having also been already vastly used in archeology and experimentally in the historical-artistic field on mobile artifacts such as canvases and boards.

Thanks to a long research process, it was possible to adapt this software to graphic documentation problems and to validate a series of chain operations which could be modelled into a Plugin or a processing model. As for image analysis, currently QGIS is lacking some functions as compared to Matlab; for example, in statistic elaboration it lacks ICA algorithm and specific thresholding algorithms, which however can be easily implemented.

Even though a few useful applications have been identified, the methodology is not designed to be limited to a specific software, on the contrary, being developed through a set of vastly known algorithms, it is by nature easy to implement within software applications such as SICAR, developed for graphic documentation. In fact, methodology was purposely divided into two distinct phases, and in the currently used software the first phase, i.e. image analysis and feature extraction, is lacking. Algorithms selected for this phase can be presented through user friendly graphic interfaces, so as to provide non expert conservators/restorers with a useful and functional tool for image analysis.



Furthermore, the entire algorithm sequence has been designed to be applied to any artifact typology, and can be adapted also to tridimensional survey procedures, which still use 2D images to characterize models' texture.

The methodology progression required an interdisciplinary and collaborative approach: photographic diagnostic surveys, image analysis, historical analysis and conservation intervention projects, database design, system usability, user friendliness, etc. were all approached by referring to various disciplines and specific knowledge, involving the profiles of diagnosticians, art historians, restorers and GIS professionals.

This dissertation, approaching graphic documentation from the point of view of restorers, aims to interact also with other fields of knowledge, with the purpose of cooperating and sharing goals and strategies.

Nowadays relations between Cultural heritage and technological innovation are very productive, however scientific research in the field of documentation often goes in chase of advanced technology, without actually reflecting on their usability or ability to solve serious and long overlooked problems.

As for the new approach to graphic documentation offered in this dissertation, we will certainly need time to discover, analyzing case by case, which are its true limitations and improvements from the technical point of view. Nevertheless, in the author's opinion, we are moving in the right direction: in a documentation system based on visual analysis and on representation through 3D models or images, issues such as statistical analysis of digital images and features' extraction cannot be ignored.

There are still many unanswered questions concerning graphic documentation and thematic maps, such as graphic and nomenclature normalization, and a joint effort is required to create general awareness around the relevance of this discipline, which struggles to find a common denominator among all sectors of Cultural heritage; even though its relevance has always been clear, specially from the point of view of intervention projects. Concerning this last aspect, it's important

to stress that this methodology appears to be very useful and crucial in the creation of virtual iconographic restoration procedures, a.k.a. “virtual restorations”: operators applying these methodologies tend to treat the work of art’s digital image as a drawing to be retouched, often following non-scientific criteria; just as it was in the past with ancient restoration. The third study case, instead, shows how the methodology can help restorers to assess also this kind of intervention.

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